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# PHOTO SERIES FOR APPRAISING THINNING SLASH IN NORTH IDAHO

## Western Hemlock, Grand Fir, and Western Redcedar Timber Types

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Wayne H. Koski
William C. Fischer

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A COOPERATIVE
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ting from precommercial thinning operations in three north Idaho timber types. Each photo is supplemented by inventory data describing the size, weight, and volume of the debris pictured. Stand data relating to the thinning operation are provided and estimates of predicted fire behavior and Idaho Forest Practice Act slash hazard rating are given.

Instructions for using the photos to describe precommercial thinning slash and to evaluate potential fire hazard are provided.

## ACKNOWLEDGMENTS

This publication is the result of a cooperative effort between the State of Idaho, Department of Lands, and the USDA Forest Service Intermountain Forest and Range Experiment Station. The support of Mark E. Weadick, Supervisor of Forest Management Planning, State of Idaho, Department of Lands, and Dr. James E. Lotan, Program Manager, Fire in Multiple Use Research, Development and Applications Program at the Northern Forest Fire Laboratory is acknowledged.

For uniformity and user convenience, the format of this publication is patterned after the photo series for quantifying forest residues recently produced by the USDA Forest Service, Pacific Northwest Forest and Range Experiment Station (Maxwell and Ward 1976a, 1976b).

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# PHOTO SERIES FOR APPRAISING THINNING SLASH IN NORTH IDAHO:

## Western Hemlock, Grand Fir, and Western Redcedar Timber Types

**Wayne H. Koski**
**William C. Fischer**

A Cooperative Publication by
Intermountain Forest and Range Experiment Station and
the State of Idaho

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

# THE AUTHORS

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# PLANT SPECIES CITED

| | |
|---|---|
| western hemlock | *Tsuga heterophylla* (Ref.) Sarg. |
| western redcedar | *Thuja plicata* Donn. |
| grand fir | *Abies grandis* (Dongl.) Lindl. |
| western larch | *Larix occidentalis* Nutt. |
| Douglas-fir | *Pseudotsuga menziesii* (Mirb.) Franco |
| western white pine | *Pinus monticola* Dougl. |
| Engelmann spruce | *Picea engelmannii* Parry |

# METRIC CONVERSIONS AND ABBREVIATION OF UNITS

inches (in) x 2.54 = centimeters (cm)
feet (ft) x 0.3048 = meters (m)
square feet (ft$^2$) x 0.092903 = square meters (m$^2$)
cubic feet (ft$^3$) x 0.02832 = cubic meters (m$^3$)
acres (ac) x 4046.87 = square meters (m$^2$)
x 0.4047 = hectares (ha)
square feet/acre (ft /ac) x 0.22956 = square meters/hectare (m /ha)
cubic feet/acre (ft /ac) x 0.06997 = cubic meters/hectare (m /ha)
tons/acre (T/ac) x 2.2416 = metric tons/hectare (T/ha)
x 0.22417 = kilograms/square meter (kg/m )
miles/hour (mi/h x 1.7093 = kilometers/hour (km/h)
chains/hour (ch/h) x 20.1168 = meters/hour (m/h)
British thermal units/foot/second
(Btu/ft/s) x 3.4592 = kilowatts/meter (kw/m)

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# PURPOSE OF PHOTO SERIES

Thinning slash is the woody debris dropped on the forest floor during cuttings to reduce stocking in young forest stands--a practice commonly called "precommercial thinning." This debris is made up of stems, branches, twigs, and needles of the trees cut during the thinning operation. The thinning slash is laid down over the woody debris that has accumulated over the life of the stand, either from natural events or from previous forestry operations. Together, the accumulated debris and the slash can create a hazardous fuel situation that must be dealt with by the fire manager.

The purpose of this photo series is to help the forest manager determine the fire hazard associated with thinning slash and decide if treatment is needed. The photos show different slash fuel situations created as a result of precommercial thinning in three timber types common in north Idaho.

The fuel complex shown in each photo is described on an accompanying data sheet in terms of:

1. Physical characteristics.
2. The stand and its thinning prescription.
3. Potential fire behavior.
4. Idaho Forest Practice Act slash hazard rating.

We propose that the manager use these photos to evaluate similar slash situations, thereby saving the cost of field inventory and data analysis.

The most important reason for evaluating thinning slash is to decide if the slash presents an unacceptable fire hazard to the selected crop trees or to the surrounding forest area. If the hazard is judged unacceptable, the photos can be used to decide the amount and type of treatment, the priority of treatment among several areas, and the amount of protection needed until hazard has been abated.

Because the photos show the results of different thinning prescriptions, they can be useful for planning thinning operations. Undesirable thinning prescriptions can be recognized in advance of cutting and avoided by changing the prescription, planning fuel reduction as a part of the thinning operation, or selecting different areas for thinning. As a planning aid, the photos are best used in conjunction with other precutting planning aids such as debris prediction and hazard appraisal procedures suggested by Albini and others (1977), by Brown and others (1977), and by Koski (1977a, 1977b). For example, the debris prediction technique developed by Brown and others (1977), predicts the amount of slash that will result from a planned thinning. The only information needed is the number of trees to be cut by species and size class. This photo series can be used to visualize the slash loads predicted with Brown's technique and can provide a basis for discussing appropriate fuel management actions.

# USING THE PHOTOS

## Describing the Fuel Complex

Two important characteristics of the fuel complex can be seen in each photo: (1) The weight of fuel in the different diameter classes, and (2) the percentage of ground covered by fuel. Consequently, the manager can use the photos to estimate rough values for these characteristics of thinning slash. Fuel depth can be estimated from the black and white pole of the plot marker. Each black and white section is 1 foot (0.3048 m).

To use the photos to describe thinning slash, simply inspect the fuel complex and then select the photo that most nearly compares with what is seen on the ground. Then use the information on the data sheet to describe the fuel complex.

Perhaps no one photo adequately represents the actual situation. If this is the case, select two successive photos that bracket the observed fuel complex and then interpolate between the values on the data sheets accompanying the selected photos.

Rather than try to select one photo, or a pair of photos that best reflect the entire fuel complex, the user can describe each of the three above-mentioned characteristics separately. This can be done by using the following procedure suggested by Maxwell and Ward (1976a, 1976b):

1. Observe each of the characteristics of the fuel complex on-the-ground (loading by size class, and percentage of ground covered).
2. For each characteristic, select the photo that most nearly matches, or photos that bracket the observed situation.
3. For each characteristic, obtain a value from the data sheet accompanying the selected photo (or interpolate a value if a pair of photos was selected).

On large areas of slash, zones of different slash loadings are often apparent. In such cases each zone should be described and evaluated separately. The results can then be weighted and cumulated for the whole area.

Some characteristics of the fuel complex, especially those associated with the accumulated debris, cannot be easily observed from the photo. If needed, values for such characteristics as the size and condition of larger woody material must be taken "on faith" from the data sheet accompanying the selected photo or obtained from field sampling or observation.

## Appraising Potential Fire Behavior

The data sheet for each photo contains potential fire behavior values for the pictured fuel complex. The fire behavior predictions are based on the measured fuel loadings for each stand. Low fuel moisture is assumed; 0-0.25 inch (0-0.64 cm) diameter. fuel moisture content = 5 percent. Predictions are given for three different 20-foot (6.1-m) windspeeds; 0, 10, and 20 mi/h (0, 16.1, and 32.2 km/h); and three slash ages (1, 3, and 5 years after cutting). Because actual slope is not evident in the photos, 20 percent slope is assumed for all stands. The wind and resulting fire spread are assumed to be upslope. The fuel is assumed to be spread uniformly over the site. The differences between predicted fire behavior between years 1 and 3, and years 3 and 5, represent the effect of needle fall and settling of the slash over time.

Six different expressions of fire behavior are shown on the data sheet. A description of each follows, along with comparative values and other aids to help the user interpret them (Albini and others 1977).

1. *Head fire rate of spread (ch/h)*.--The values under this heading are maximum rates, rounded to the nearest ch/h; the wind is blowing directly upslope, and the fire is advancing upslope. For comparison purposes, note the following equivalent rates of progress:

- 1 ch/h (about 20 m/h) is about the rate of fireline construction for one man using hand tools in medium fuels (medium resistance to control).
- 10 ch/h (about 200 m/h) is about the rate of fireline construction for a bulldozer working in fuels of extreme resistance to control.
- 100 ch/h (about 2,000 m/h) is about the speed of a leisurely stroll on level terrain or a good average pace for backpacking in medium to steep terrain.

2. *Perimeter growth rate (ch/h)*.--Under the conditions cited above, this value is an estimate of the rate of increase in the length of a smooth elliptical outline marking the advancing edge of a fire started at a point (a spotfire) in the slash. The perimeter growth rate can be viewed as a rough indication of the minimum total line-building rate required to contain a fire.

3. *Area burned in 1 hour (acres)*.--This value tells the area burned after 1 hour. The value can be used to predict how long a fire that starts in the slash will stay in the slash. Burned area increases with the square of the burning time. To predict the time a fire would stay in the thinning unit, divide half the area of the thinning unit by the area burned in 1 hour and take the square root. The result will be the time, in hours, that one could expect the fire to be burning mostly in the thinning slash. After this period of time, a fire started in the unit would probably have burned out of it into adjacent fuels.

4. *Head fire flame length (feet)*.--This is the length of flame from the center of the flaming zone at the upper surface of the slash to the tip of the flame. This dimension, with no wind, will be the

vertical flame height. In most cases, wind will tilt the flame and the flame length will be the slant distance. Guides for interpreting flame length are included under item 6, below.

5. *Crown scorch height due to head fire (feet)*.--Crown scorch height is calculated from Byram's intensity (see item 6 below). The scorch height value represents the height at which a lethal temperature of 140°F (60°C) or greater is reached above a spreading head fire. Values are rounded to the nearest foot and assume an ambient temperature of 77°F (25°C). Although it is possible to adjust for other ambient temperatures (Albini 1976b), the accuracy of the estimate in itself does not warrant such a refinement. Lethal scorching implies that the tissue is killed; the scorched needles will turn brown within a few weeks. Cambium kill due to heating alone (with or without crown scorch) is not provided in this assessment. Thus, the user should be aware that tree kill may be underestimated if only crown scorch is considered.

6. *Byram's intensity for the head fire (Btu/ft/s)*.--This quantity represents the rate of heat release per foot of fire edge at the head of the running fire. It has been used to describe the difficulty of controlling a fire. The list that follows shows numerical values and associated descriptions that may help to interpret this quantity. The flame length (item 4, above) derived for each intensity from Byram's formula is also shown.

| *Byram's intensity* | *Flame length* | *Fire situation* |
|---|---|---|
| ≤ 5 Btu/ft/s<br>(≤ 17 kw/m) | ≤ 1 ft<br>(0.3 m) | Marginal burning. Few fires exist at this level. |
| 20 - 50 Btu/ft/s<br>(69 - 173 kw/m) | 2 - 3 ft<br>(0.6 - 0.9 m) | Easily attacked and controlled. People can work right up to the edge of the fire without extra protection. |
| 100 Btu/ft/s<br>(346 kw/m) | 4 ft<br>(1.2 m) | This is about the limit beyond which people are unable to work at the fire edge. Direct attack with hand crews may be difficult. |

(con.)

6. (con.)

| | | |
|---|---|---|
| 500 - 700 Btu/ft/s<br>(1,730 - 2,421 kw/m) | 8 - 9 ft<br>(2.4 - 2.7 m) | Spotting becomes a problem and the limit of direct attack is probably reached in this range of intensities. |
| 1,000 Btu/ft/s<br>(3,459 kw/m) | 11 ft<br>(3.4 m) | Crowning can be expected to begin. Serious spotting may occur. |
| 20,000 - 30,000 Btu/ft/s<br>(69,184 - 103,800 kw/m) | 40 - 50 ft<br>(12.2 - 15.1 m) | Major conflagration. Long-range spotting occurs; tree blowdown may occur. Flaming zone depths of up to 1/4 mile (0.4 km) can arise, so the flame length formula is not very useful here. |

The values predicted for various fire parameters are only approximations, but nevertheless provide a valuable estimate of fire behavior under comparable conditions.

## Rating Slash Hazard

The Idaho Forest Practice Act (State of Idaho 1977) requires that planned thinning operations be evaluated by use of a slash hazard rating system that assigns points for various hazard characteristics and deducts points for ameliorating factors. If the total points assigned to a planned thinning project exceed a specified value, the project must be modified and slash disposal or other hazard abatement practices must be included in the plan. Hazard characteristics to which points are assigned are predicted fuel quantity, size of area, slope and aspect, prethinning stand and fuel situation, and time of year work is planned. Offsetting factors include planned slash disposal and treatment, fire and fuelbreak construction, access, availability of water, suppression capability, and special detection and prevention measures.

Fuel quantity as used in the Act, refers to the fuel created as a result of thinning. It does not include fuel that was on the ground before thinning. Up to 60 hazard points can be assigned to a planned thinning for fuel quantity. The exact score depends on the number of trees to be cut and their average diameter. Included in the Act is a hazard table that tells the number of hazard points for fuel quantity for any given combination of average diameter and number of trees to be cut.

Fuel quantity hazard points are given for each photo. Consequently, raters can use the photos to help visualize the relationship between the size and number of stems cut, the resulting fuel load, and the slash hazard points for fuel quantity. The rater must remember, however, that the fuel quantity slash hazard points are only a part of the total points assigned to a precommercial thinning. Other hazard points for slope and aspect, area size, and natural fuel quantities must also be evaluated to obtain total hazard points.

## PHOTO SERIES DEVELOPMENT

This photo series is an example of how current research can be applied to a specific management problem. The tasks involved in developing this photo series and the sources of information are as follows:

1. The areas photographed were selected to represent different fuel loading levels typical of precommercial thinning slash in western hemlock, grand fir, and western redcedar stands in north Idaho.

2. Sample plots were laid out and photographed in accordance with procedures suggested by USDA Forest Service (1975) and by Fischer.[1]

3. Fuels were described by using field inventory and computation techniques developed by Brown (1974).

---

[1] Fischer, William C. 1977. Progress report: Fire potential rating technique for fuel management planning guidelines. 13 p. North. For. Fire Lab., Missoula, MT 59806.

4. Information describing the precommercial thinning prescription was obtained from stand data in the project files.

5. Potential fire behavior was assessed using fire modeling techniques developed by Rothermel (1972) and Albini (1976a) and fuel appraisal techniques developed by Brown (1977).

6. Slash hazard points for fuel quantity are based on the guidelines contained in Rule 817.03, Idaho Forest Practice Act, Title 38, Chapter 13, Idaho Code.

# PHOTO SERIES CODING

This booklet is arranged so that a photo and the corresponding data sheet are on facing pages. When positioned for viewing, the photo is on the top and the data sheet on the bottom. Both photo and corresponding data sheet have the same code. The code is patterned after the one used by Maxwell and Ward (1976a, 1976b). The code shows:

a. Order or rank, from lightest loading to heaviest loading, in the series of photographs. 1 = lightest load in each forest type series.

b. Forest type, e.g., WH = western hemlock, GF = grand fir, WC = western cedar, WL = western larch, WWP = western white pine, ES = Engelmann spruce, DF = Douglas-fir.

c. Forest size class, where: 1 = < 6-inch (< 15.24-cm) d.b.h.

d. Cutting practice, where: TH = precommercial thinning.

*Example:* *1-WH-1-TH is the first photo in the series of western hemlock, < 6-inch (< 15.24 cm) diameter trees, precommercial thinning.*

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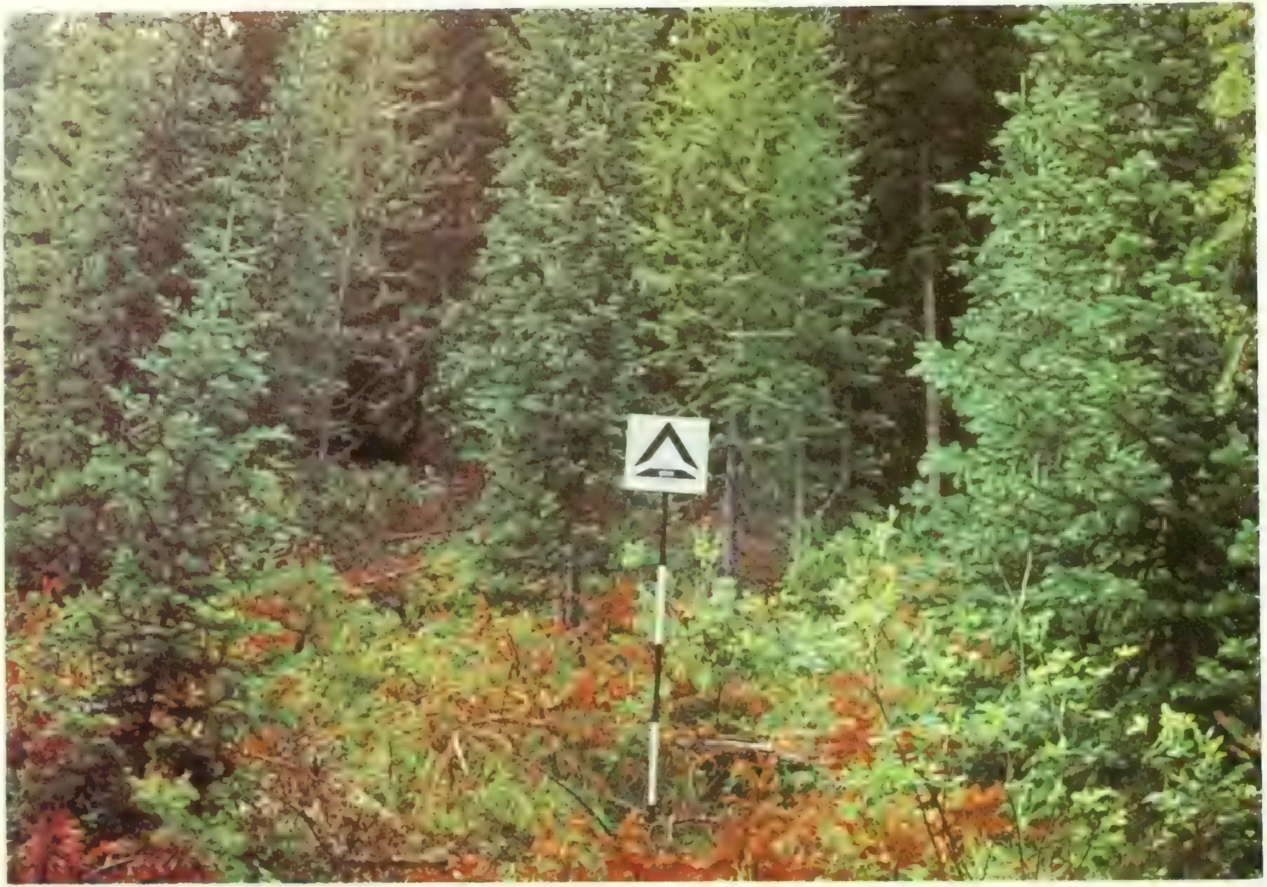
# WESTERN HEMLOCK
# SIZE CLASS 1
# PRECOMMERCIAL THINNING

**Reminders to users:**

1. The marker in these photos is 1 foot (0.3048 m) square, and the pole is painted in contrasting colors at 1-foot (0.3048-m) intervals to provide scale.
2. Stumps are not included in debris quantities.
3. Rotten debris is that which would come apart or splinter when kicked.
4. Potential fire behavior is for low fuel moisture and 20% slope.
5. Windspeed is taken at 20 feet (6.1 m) above the ground.



1-WH-1-TH

## DATA SHEET

CODE: 1-WH-1-TH

### DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 0.8 | 0.8 |
| 0.25-1.0 | 0.9 | 0.9 |
| 1.1-3.0 | 1.8 | 2.0 |
| 3.1-10.0 | 0 | 5.8 |
| 10.1-20.0 | 0 | 0 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 3.5 | 9.5 |
| TOTAL *(kg/m$^2$)* | *(0.78)* | *(2.13)* |

### UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 619 ft$^3$/ac *(43.3 m$^3$/ha)*

Percent sound 0 %

Percent rotten 100 %

Avg. diameter:

sound -- in

Sound & rotten 6.4 in *(16.3 cm)*

### POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 1 | 0.5 | 0.3 |
| | 10 | 22 | 10 | 5 |
| | 20 | 73 | 29 | 13 |
| Perimeter Growth rate (ch/h) | 0 | 4 | 2 | 1 |
| | 10 | 41 | 10 | 5 |
| | 20 | 41 | 10 | 5 |
| Burned area After 1 h (acres) | 0 | 0.1 | 0.03 | 0.01 |
| | 10 | 8 | 0.5 | 0.1 |
| | 20 | 8 | 0.5 | 0.1 |
| Head fire Flame length (feet) | 0 | 0.6 | 0.4 | 0.4 |
| | 10 | 3 | 2 | 1 |
| | 20 | 5 | 3 | 2 |
| Crown scorch By head fire (feet) | 0 | 2 | 1 | 0.7 |
| | 10 | 3 | 1 | 0.5 |
| | 20 | 4 | 1 | 0.5 |
| Head fire Intensity (Btu/ft/s) | 0 | 2 | 1 | 0.6 |
| | 10 | 48 | 16 | 10 |
| | 20 | 159 | 47 | 26 |

### PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 2354 (Avg. d.b.h. 1") |
| Stems remaining per acre | 436 |
| Average d.b.h. before (inches) | 1 |
| Average d.b.h. after (inches) | 4 |
| Basal area/acre before | 63 |
| Basal area/acre after | 38 |
| Thinning method | Chainsaw |
| Slash treatment | None |

### OTHER INFORMATION

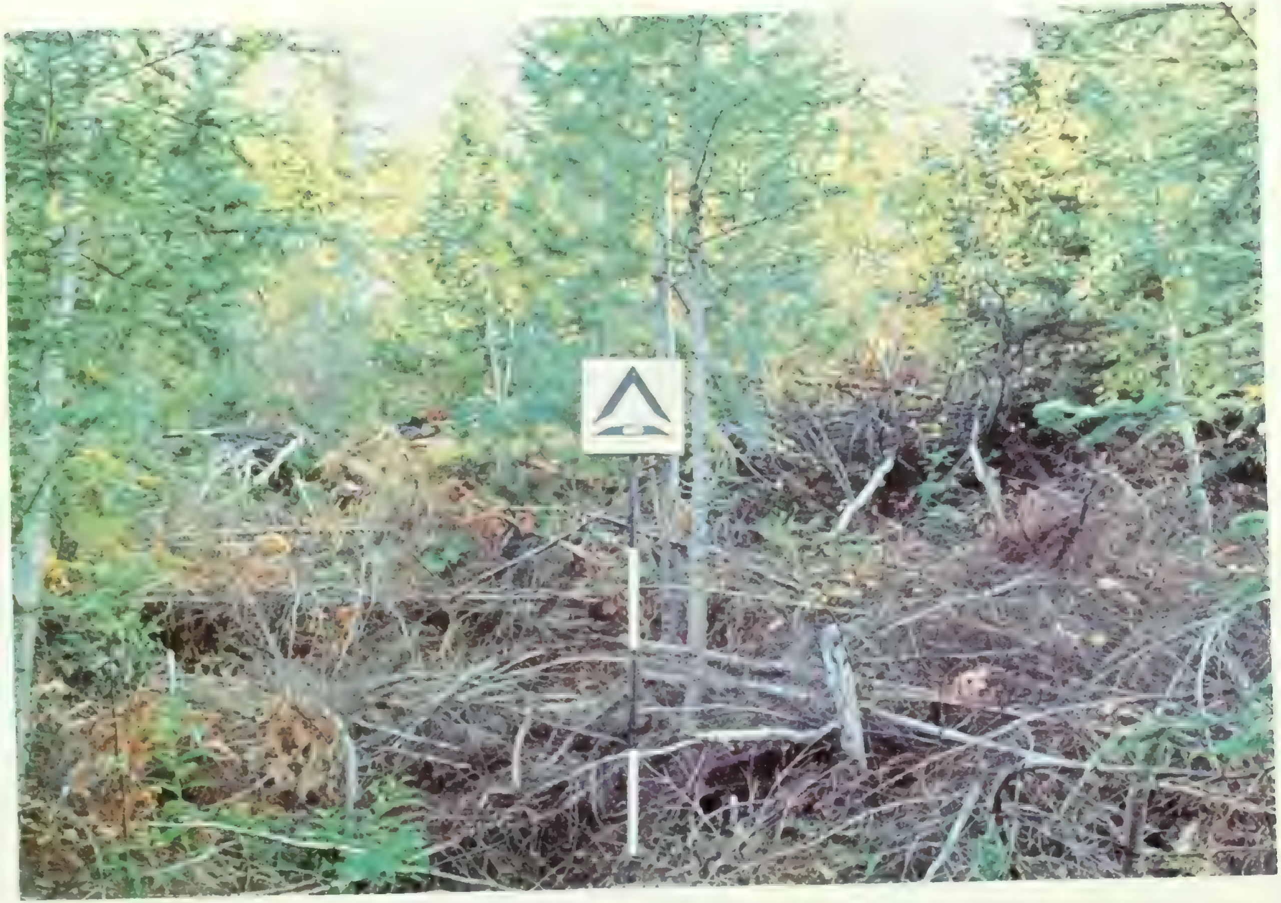
Slash age 3 months

Average slope 50 percent

Species composition: WH 50%, WL 50%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 10



2-WH-1-TH

## DATA SHEET

CODE: 2-WH-1-TH

### DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 2.2 | 2.2 |
| 0.25-1.0 | 3.4 | 4.1 |
| 1.1-3.0 | 7.9 | 10.1 |
| 3.1-10.0 | 0.1 | 2.8 |
| 10.1-20.0 | 0 | 27.8 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 13.6 | 47.0 |
| TOTAL *(kg/m$^2$)* | *(3.05)* | *(10.54)* |

### UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 3267 ft$^3$/ac *(228.6 m$^3$/ha)*

Percent sound 0 %

Percent rotten 100 %

Avg. diameter:

sound -- in

Sound & rotten 13.1 in *(33.3 cm)*

### POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 1 | 1 | 0.7 |
| | 10 | 30 | 15 | 9 |
| | 20 | 96 | 44 | 20 |
| Perimeter Growth rate (ch/h) | 0 | 6 | 4 | 3 |
| | 10 | 79 | 40 | 22 |
| | 20 | 220 | 74 | 36 |
| Burned area After 1 h (acres) | 0 | 0.3 | 0.1 | 0.1 |
| | 10 | 31 | 8 | 2 |
| | 20 | 95 | 11 | 3 |
| Head fire Flame length (feet) | 0 | 1 | 1 | 1 |
| | 10 | 5 | 3 | 3 |
| | 20 | 8 | 6 | 5 |
| Crown scorch By head fire (feet) | 0 | 4 | 3 | 3 |
| | 10 | 13 | 5 | 4 |
| | 20 | 18 | 6 | 4 |
| Head fire Intensity (Btu/ft/s) | 0 | 9 | 5 | 5 |
| | 10 | 185 | 82 | 62 |
| | 20 | 584 | 236 | 148 |

### PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 7900 (Avg. d.b.h. 1") |
| Stems remaining per acre | 436 |
| Average d.b.h. before (inches) | 1 |
| Average d.b.h. after (inches) | 2 |
| Basal area/acre before | 53 |
| Basal area/acre after | 10 |
| Thinning method | Chainsaw |
| Slash treatment | None |

### OTHER INFORMATION

Slash age 12 months

Average slope 60 percent

Species composition: WH 80%, GF 20%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 32

3-WH-1-TH

## DATA SHEET

CODE: 3-WH-1-TH

### DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 2.7 | 2.7 |
| 0.25-1.0 | 3.5 | 3.5 |
| 1.1-3.0 | 8.5 | 8.6 |
| 3.1-10.0 | 1.2 | 18.3 |
| 10.1-20.0 | 0 | 16.0 |
| 20.1+ | 0 | 13.8 |
| TOTAL tons/acre | 15.9 | 62.9 |
| TOTAL *(kg/m²)* | *(3.56)* | *(14.10)* |

### UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 5104 ft³/ac
*(357.1 m³/ha)*

Percent sound 3 %

Percent rotten 97 %

Avg. diameter:

sound 3.4 in
*(8.6 cm)*

Sound & rotten 8.6 in
*(21.8 cm)*

### POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 2 | 1 | 1 |
| | 10 | 53 | 24 | 13 |
| | 20 | 172 | 72 | 34 |
| Perimeter Growth rate (ch/h) | 0 | 10 | 5 | 4 |
| | 10 | 137 | 62 | 34 |
| | 20 | 393 | 142 | 66 |
| Burned area After 1 h (acres) | 0 | 1 | 0.2 | 0.1 |
| | 10 | 93 | 19 | 6 |
| | 20 | 304 | 40 | 9 |
| Head fire Flame length (feet) | 0 | 2 | 1 | 1 |
| | 10 | 7 | 4 | 4 |
| | 20 | 12 | 7 | 6 |
| Crown scorch By head fire (feet) | 0 | 6 | 4 | 3 |
| | 10 | 27 | 9 | 6 |
| | 20 | 42 | 12 | 7 |
| Head fire Intensity (Btu/ft/s) | 0 | 16 | 7 | 6 |
| | 10 | 381 | 135 | 96 |
| | 20 | 1237 | 403 | 243 |

### PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 2836 (Avg. d.b.h. 2") |
| Stems remaining per acre | 436 |
| Average d.b.h. before (inches) | 2 |
| Average d.b.h. after (inches) | 4 |
| Basal area/acre before | 100 |
| Basal area/acre after | 38 |
| Thinning method | Chainsaw |
| Slash treatment | None |

### OTHER INFORMATION

Slash age 4 months

Average slope 30 percent

Species composition: WH 100%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 41

4-WH-1-TH

## DATA SHEET

CODE: 4-WH-1-TH

### DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 4.3 | 4.3 |
| 0.25-1.0 | 6.6 | 6.6 |
| 1.1-3.0 | 16.0 | 17.5 |
| 3.1-10.0 | 0.6 | 6.0 |
| 10.1-20.0 | 0 | 50.5 |
| 20.1+ | 0 | 4.7 |
| TOTAL tons/acre | 27.5 | 89.6 |
| TOTAL (kg/m²) | (6.16) | (20.09) |

### UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 6455 ft³/ac (451.7 m³/ha)

Percent sound 10 %

Percent rotten 90 %

Avg. diameter:

sound 5.8 in (14.7 cm)

Sound & rotten 10.2 in (25.9 cm)

### PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 4627 (Avg. d.b.h. 2") |
| Stems remaining per acre | 436 |
| Average d.b.h. before (inches) | 2 |
| Average d.b.h. after (inches) | 4 |
| Basal area/acre before | 139 |
| Basal area/acre after | 38 |
| Thinning method | Chainsaw |
| Slash treatment | None |

### OTHER INFORMATION

Slash age 4 months

Average slope 0 percent

Species composition: WH 100%

### POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 2 | 1 | 1 |
| | 10 | 41 | 19 | 9 |
| | 20 | 132 | 55 | 23 |
| Perimeter Growth rate (ch/h) | 0 | 9 | 5 | 3 |
| | 10 | 107 | 49 | 24 |
| | 20 | 303 | 125 | 46 |
| Burned area After 1 h (acres) | 0 | 1 | 0.2 | 0.1 |
| | 10 | 57 | 12 | 3 |
| | 20 | 180 | 31 | 4 |
| Head fire Flame length (feet) | 0 | 2 | 1 | 1 |
| | 10 | 7 | 4 | 3 |
| | 20 | 12 | 7 | 5 |
| Crown scorch By head fire (feet) | 0 | 7 | 4 | 3 |
| | 10 | 26 | 8 | 4 |
| | 20 | 39 | 10 | 5 |
| Head fire Intensity (Btu/ft/s) | 0 | 18 | 7 | 6 |
| | 10 | 363 | 123 | 72 |
| | 20 | 1161 | 358 | 176 |

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 58

5-WH-1-TH

## DATA SHEET

CODE: 5-WH-1-TH

### DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 5.2 | 5.2 |
| 0.25-1.0 | 5.1 | 5.1 |
| 1.1-3.0 | 13.2 | 13.2 |
| 3.1-10.0 | 3.5 | 9.5 |
| 10.1-20.0 | 0 | 2.3 |
| 20.1+ | 0 | 5.6 |
| TOTAL tons/acre | 27.0 | 40.9 |
| TOTAL *(kg/m²)* | *(6.05)* | *(9.17)* |

### UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 1764 $ft^3$/ac
*(123.4 $m^3$/ha)*

Percent sound 20 %

Percent rotten 80 %

Avg. diameter:

sound 3.3 in
*(8.4 cm)*

Sound & rotten 5.3 in
*(13.5 cm)*

### POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 2 | 1 | 0.7 |
| | 10 | 49 | 22 | 10 |
| | 20 | 179 | 66 | 26 |
| Perimeter Growth rate (ch/h) | 0 | 11 | 5 | 3 |
| | 10 | 141 | 56 | 26 |
| | 20 | 409 | 150 | 43 |
| Burned area After 1 h (acres) | 0 | 1 | 0.2 | 0.1 |
| | 10 | 98 | 15 | 3 |
| | 20 | 329 | 44 | 4 |
| Head fire Flame length (feet) | 0 | 2 | 1 | 1 |
| | 10 | 8 | 4 | 3 |
| | 20 | 14 | 7 | 5 |
| Crown scorch By head fire (feet) | 0 | 8 | 4 | 3 |
| | 10 | 38 | 9 | 4 |
| | 20 | 61 | 12 | 4 |
| Head fire Intensity (Btu/ft/s) | 0 | 24 | 7 | 4 |
| | 10 | 532 | 132 | 60 |
| | 20 | 1745 | 400 | 157 |

### PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 5015 (Avg. d.b.h. 2") |
| Stems remaining per acre | 436 |
| Average d.b.h. before (inches) | 2 |
| Average d.b.h. after (inches) | 4 |
| Basal area/acre before | 147 |
| Basal area/acre after | 38 |
| Thinning method | Chainsaw |
| Slash treatment | None |

### OTHER INFORMATION

Slash age 4 months

Average slope 50 percent

Species composition: GF 40%, WL 30%, WH 20%, ES 10%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 60

6-WH-1-TH

CODE: 6-WH-1-TH

## DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) | |
|---|---|---|
| | Slash Only | Total Debris |
| 0-0.25 | 4.9 | 4.9 |
| 0.25-1.0 | 4.9 | 4.9 |
| 1.1-3.0 | 11.1 | 11.4 |
| 3.1-10.0 | 4.2 | 17.3 |
| 10.1-20.0 | 0 | 6.2 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 25.1 | 44.7 |
| TOTAL ($kg/m^2$) | (5.63) | (10.02) |

## UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 2230 $ft^3/ac$ (156.0 $m^3/ha$)

Percent sound 44 %

Percent rotten 56 %

Avg. diameter:

sound 3.5 in (8.9 cm)

Sound & rotten 4.5 in (11.4 cm)

## PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 5642 (Avg. d.b.h. 2") |
| Stems remaining per acre | 436 |
| Average d.b.h. before (inches) | 2 |
| Average d.b.h. after (inches) | 4 |
| Basal area/acre before | 161 |
| Basal area/acre after | 38 |
| Thinning method | Chainsaw |
| Slash treatment | None |

## OTHER INFORMATION

Slash age 2 months

Average slope 50 percent

Species composition: WH 70%, WL 20%, ES 10%

## POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 2 | 1 | 0.6 |
| | 10 | 50 | 20 | 9 |
| | 20 | 165 | 59 | 23 |
| Perimeter Growth rate (ch/h) | 0 | 10 | 4 | 3 |
| | 10 | 130 | 51 | 23 |
| | 20 | 377 | 119 | 32 |
| Burned area After 1 h (acres) | 0 | 1 | 0.2 | 0.05 |
| | 10 | 83 | 13 | 3 |
| | 20 | 280 | 28 | 3 |
| Head fire Flame length (feet) | 0 | 2 | 1 | 1 |
| | 10 | 8 | 4 | 3 |
| | 20 | 13 | 6 | 4 |
| Crown scorch By head fire (feet) | 0 | 8 | 3 | 2 |
| | 10 | 33 | 7 | 3 |
| | 20 | 51 | 9 | 3 |
| Head fire Intensity (Btu/ft/s) | 0 | 21 | 6 | 3 |
| | 10 | 451 | 107 | 46 |
| | 20 | 1482 | 326 | 121 |

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 60

# GRAND FIR
# SIZE CLASS 1
# PRECOMMERCIAL THINNING

**Reminders to users:**

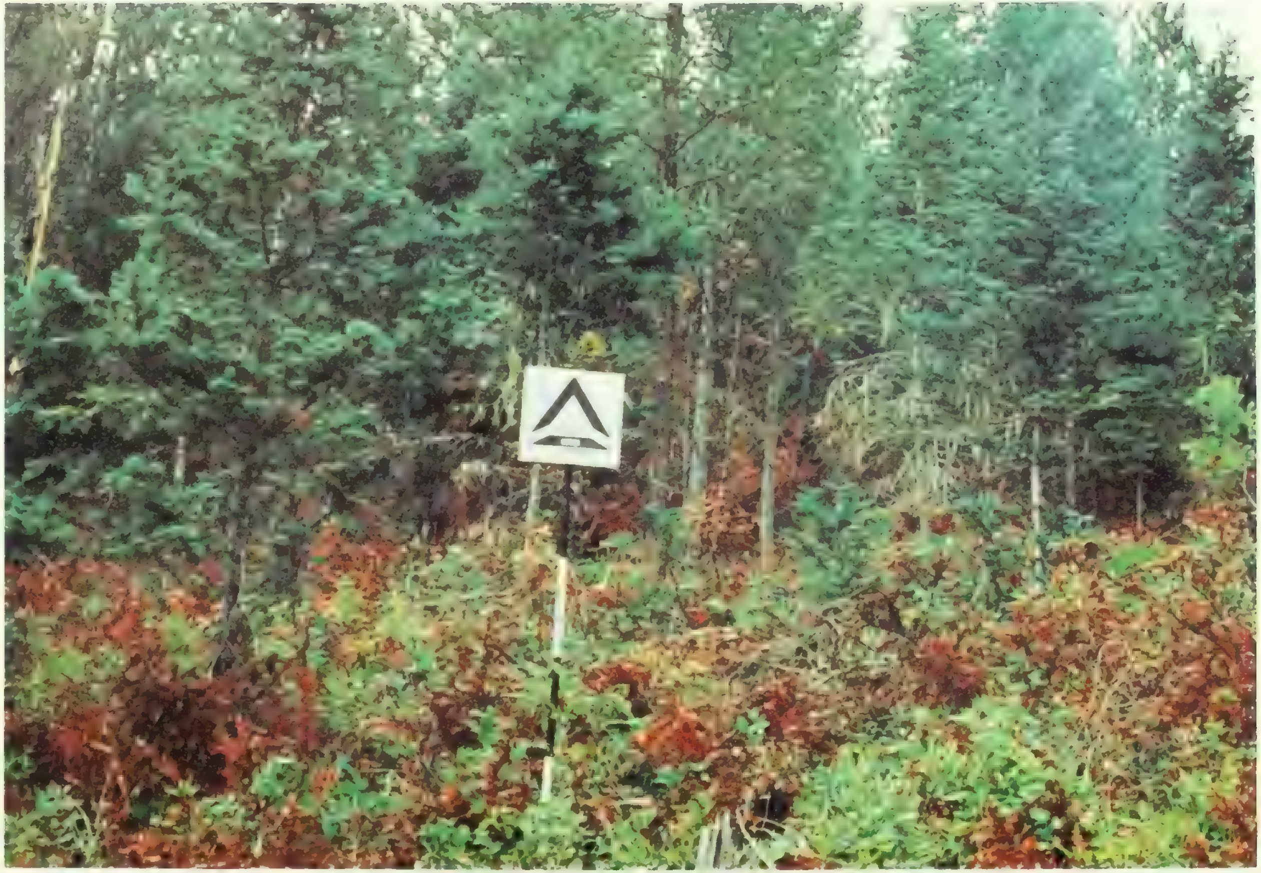
1. The marker in these photos is 1 foot (0.3048 m) square, and the pole is painted in contrasting colors at 1-foot (0.3048-m) intervals to provide scale.

2. Stumps are not included in debris quantities.

3. Rotten debris is that which would come apart or splinter when kicked.

4. Potential fire behavior is for low fuel moisture and 20% slope.

5. Windspeed is taken at 20 feet (6.1 m) above the ground.



1-GF-1-TH

CODE: 1-GF-1-TH

## DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 1.6 | 1.6 |
| 0.25-1.0 | 1.6 | 2.4 |
| 1.1-3.0 | 1.9 | 3.2 |
| 3.1-10.0 | 0 | 1.4 |
| 10.1-20.0 | 0 | 0 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 5.1 | 8.6 |
| TOTAL *(kg/m²)* | *(1.14)* | *(1.93)* |

## UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 150 ft$^3$/ac *(10.5 m$^3$/ha)*

Percent sound 0 %

Percent rotten 100 %

Avg. diameter:

sound — in

Sound & rotten 3.4 in *(8.6 cm)*

## PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 3396 (Avg. d.b.h. < 1") |
| Stems remaining per acre | 440 |
| Average d.b.h. before (inches) | 1 |
| Average d.b.h. after (inches) | 3 |
| Basal area/acre before | 48 |
| Basal area/acre after | 29 |
| Thinning method | Chainsaw |
| Slash treatment | None |

## OTHER INFORMATION

Slash age 12 months

Average slope 40 percent

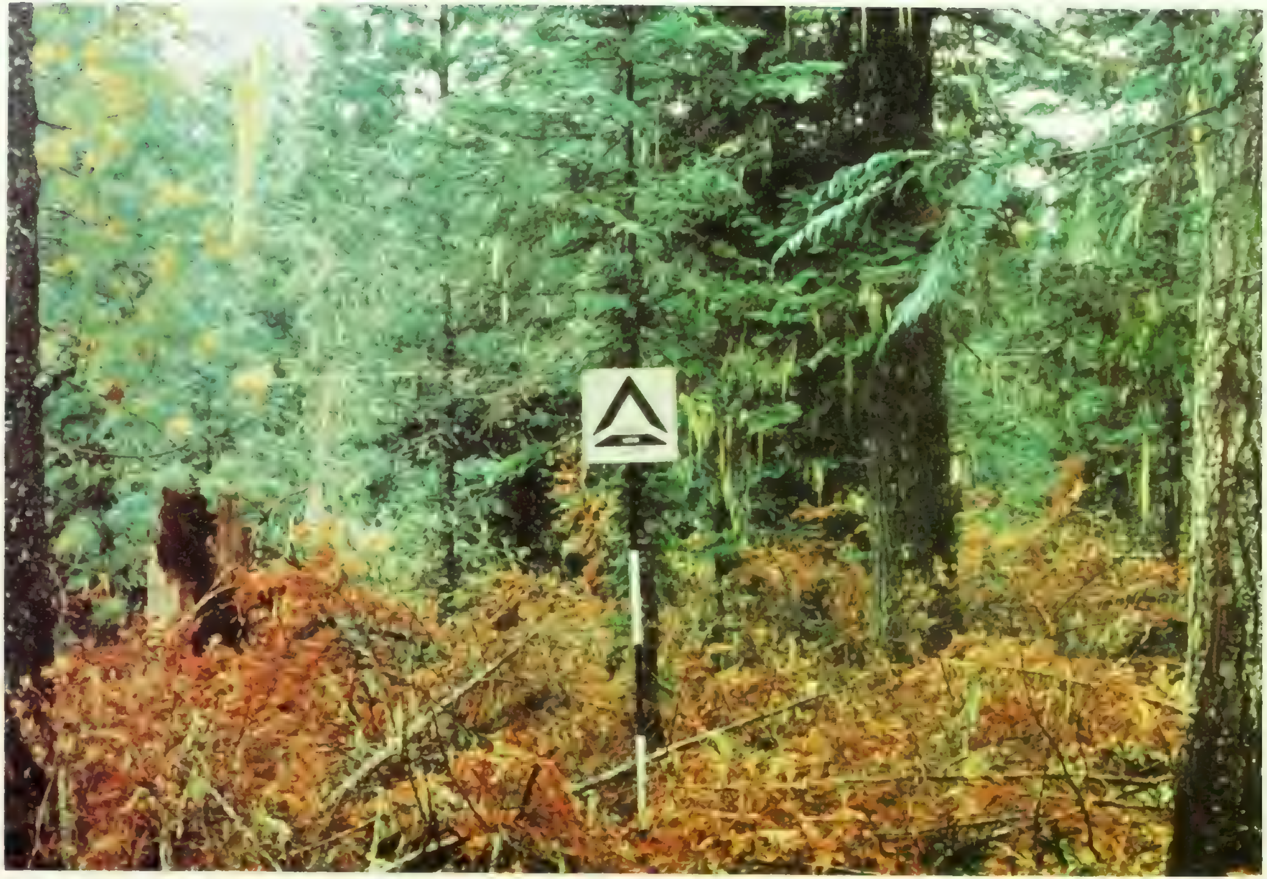
Species composition: GF 100%

## POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 0.6 | 0.3 | 0.2 |
| | 10 | 10 | 4 | 2 |
| | 20 | 27 | 11 | 5 |
| Perimeter Growth rate (ch/h) | 0 | 3 | 1 | 2 |
| | 10 | 27 | 9 | 19 |
| | 20 | 35 | 9 | 21 |
| Burned area After 1 h (acres) | 0 | .05 | 0.01 | 0.01 |
| | 10 | 3 | 0.4 | 0.1 |
| | 20 | 3 | 0.4 | 0.1 |
| Head fire Flame length (feet) | 0 | 1 | 0.5 | 0.4 |
| | 10 | 3 | 2 | 1 |
| | 20 | 4 | 2 | 2 |
| Crown scorch By head fire (feet) | 0 | 2 | 1 | 1 |
| | 10 | 3 | 1 | 0.5 |
| | 20 | 3 | 1 | 0.5 |
| Head fire Intensity (Btu/ft/s) | 0 | 3 | 1 | 1 |
| | 10 | 51 | 15 | 10 |
| | 20 | 135 | 38 | 21 |

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 18



2-GF-1-TH

CODE: 2-GF-1-TH

## DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 2.2 | 2.2 |
| 0.25-1.0 | 1.5 | 2.6 |
| 1.1-3.0 | 4.9 | 6.9 |
| 3.1-10.0 | 0 | 1.5 |
| 10.1-20.0 | 0 | 1.9 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 8.6 | 15.1 |
| TOTAL (kg/m²) | (1.93) | (3.38) |

## UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 364 ft$^3$/ac
(25.5 m$^3$/ha)

Percent sound 0 %

Percent rotten 100 %

Avg. diameter:

sound -- in

Sound & rotten 6.1 in
(15.5 cm)

## POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 1 | 0.7 | 0.6 |
| | 10 | 23 | 11 | 7 |
| | 20 | 60 | 27 | 14 |
| Perimeter Growth rate (ch/h) | 0 | 5 | 3 | 2 |
| | 10 | 58 | 28 | 17 |
| | 20 | 137 | 45 | 25 |
| Burned area After 1 h (acres) | 0 | 0.2 | 0.1 | 0.05 |
| | 10 | 17 | 4 | 1 |
| | 20 | 37 | 4 | 1 |
| Head fire Flame length (feet) | 0 | 1 | 1 | 1 |
| | 10 | 5 | 3 | 3 |
| | 20 | 8 | 5 | 4 |
| Crown scorch By head fire (feet) | 0 | 5 | 3 | 3 |
| | 10 | 13 | 5 | 4 |
| | 20 | 16 | 5 | 3 |
| Head fire Intensity (Btu/ft/s) | 0 | 11 | 5 | 5 |
| | 10 | 193 | 73 | 60 |
| | 20 | 513 | 180 | 127 |

## PRECOMMERCIAL THINNING INFORMATION

Stems cut/acre 5472 (Avg. d.b.h. 1")
Stems remaining per acre 491
Average d.b.h. before (inches) 1
Average d.b.h. after (inches) 5
Basal area/acre before 196
Basal area/acre after 77
Thinning method Chainsaw
Slash treatment None

## OTHER INFORMATION

Slash age 3 months

Average slope 10 percent

Species composition: GF 95%, WWP 5%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 29

3-GF-1-TH

CODE: 3-GF-1-TH

## DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 3.8 | 3.8 |
| 0.25-1.0 | 2.5 | 2.7 |
| 1.1-3.0 | 4.9 | 6.0 |
| 3.1-10.0 | 5.5 | 6.2 |
| 10.1-20.0 | 0 | 0 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 16.7 | 18.7 |
| TOTAL (kg/m²) | (3.74) | (4.19) |

## UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 514 ft³/ac (36.0 m³/ha)

Percent sound 84 %

Percent rotten 16 %

Avg. diameter:

sound 3.5 in (8.9 cm)

Sound & rotten 3.5 in (8.9 cm)

## POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 2 | 1 | 0.5 |
| | 10 | 38 | 15 | 7 |
| | 20 | 104 | 39 | 17 |
| Perimeter Growth rate (ch/h) | 0 | 9 | 4 | 2 |
| | 10 | 98 | 39 | 19 |
| | 20 | 237 | 83 | 24 |
| Burned area After 1 h (acres) | 0 | 1 | 0.1 | 0.05 |
| | 10 | 47 | 8 | 2 |
| | 20 | 111 | 14 | 2 |
| Head fire Flame length (feet) | 0 | 2 | 1 | 1 |
| | 10 | 8 | 4 | 3 |
| | 20 | 12 | 6 | 4 |
| Crown scorch By head fire (feet) | 0 | 9 | 4 | 2 |
| | 10 | 34 | 7 | 3 |
| | 20 | 44 | 8 | 3 |
| Head fire Intensity (Btu/ft/s) | 0 | 26 | 7 | 4 |
| | 10 | 469 | 112 | 49 |
| | 20 | 1285 | 290 | 112 |

## PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 3084 (Avg. d.b.h. 2") |
| Stems remaining per acre | 390 |
| Average d.b.h. before (inches) | 2 |
| Average d.b.h. after (inches) | 4 |
| Basal area/acre before | 101 |
| Basal area/acre after | 34 |
| Thinning method | Chainsaw |
| Slash treatment | None |

## OTHER INFORMATION

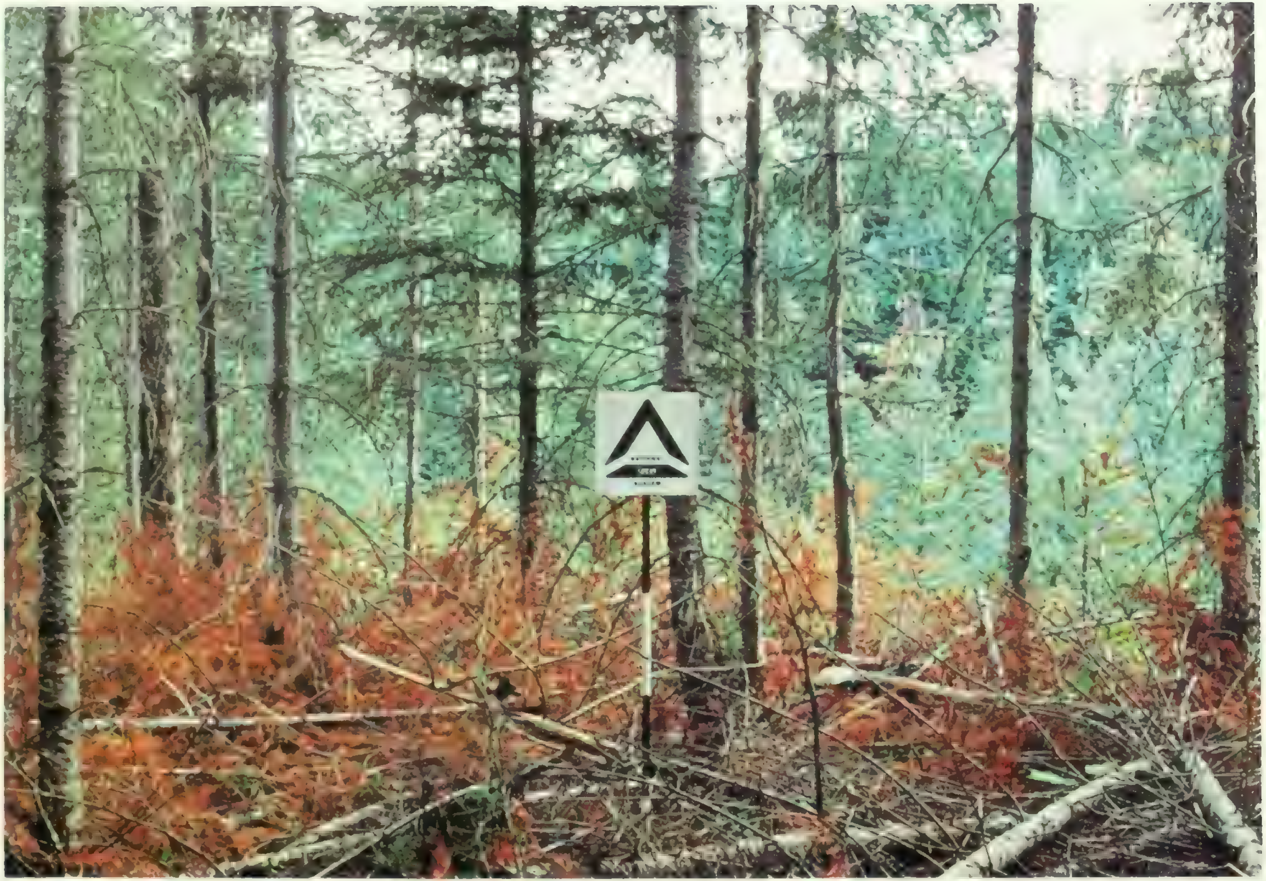
Slash age 13 months

Average slope 10 percent

Species composition: GF 70%, DF 30%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 50



4-GF-1-TH

CODE: 4-GF-1-TH

## DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) | |
|---|---|---|
| | Slash Only | Total Debris |
| 0-0.25 | 4.3 | 4.3 |
| 0.25-1.0 | 3.6 | 3.9 |
| 1.1-3.0 | 7.7 | 8.4 |
| 3.1-10.0 | 3.6 | 9.1 |
| 10.1-20.0 | 0 | 14.9 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 19.2 | 40.2 |
| TOTAL *(kg/m²)* | *(4.30)* | *(9.01)* |

## UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 2386 ft³/ac *(166.9 m³/ha)*

Percent sound 26 %

Percent rotten 74 %

Avg. diameter:

sound 3.7 in *(9.4 cm)*

Sound & rotten 5.7 in *(14.5 cm)*

## POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 2 | 1 | 1 |
| | 10 | 44 | 19 | 10 |
| | 20 | 120 | 48 | 22 |
| Perimeter Growth rate (ch/h) | 0 | 10 | 5 | 3 |
| | 10 | 115 | 48 | 26 |
| | 20 | 276 | 109 | 50 |
| Burned area After 1 h (acres) | 0 | 1 | 0.2 | 0.1 |
| | 10 | 65 | 11 | 3 |
| | 20 | 149 | 23 | 5 |
| Head fire Flame length (feet) | 0 | 2 | 1 | 1 |
| | 10 | 9 | 5 | 4 |
| | 20 | 14 | 8 | 6 |
| Crown scorch By head fire (feet) | 0 | 11 | 5 | 4 |
| | 10 | 47 | 12 | 7 |
| | 20 | 62 | 14 | 6 |
| Head fire Intensity (Btu/ft/s) | 0 | 36 | 11 | 8 |
| | 10 | 657 | 180 | 102 |
| | 20 | 1784 | 458 | 227 |

## PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 3494 (Avg. d.b.h. 2") |
| Stems remaining per acre | 390 |
| Average d.b.h. before (inches) | 2 |
| Average d.b.h. after (inches) | 4 |
| Basal area/acre before | 110 |
| Basal area/acre after | 34 |
| Thinning method | Chainsaw |
| Slash treatment | None |

## OTHER INFORMATION

Slash age 12 months

Average slope 0 percent

Species composition: GF 70%, DF 30%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 52

# WESTERN REDCEDAR
## SIZE CLASS 1
## PRECOMMERCIAL THINNING

**Reminders to users:**

1. The marker in these photos is 1 foot (0.3048 m) square, and the pole is painted in contrasting colors at 1-foot (0.3048-m) intervals to provide scale.

2. Stumps are not included in debris quantities.

3. Rotten debris is that which would come apart or splinter when kicked.

4. Potential fire behavior is for low fuel moisture and 20% slope.

5. Windspeed is taken at 20 feet (6.1 m) above the ground.

CODE: 1-WC-1-TH

## DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 0.8 | 0.8 |
| 0.25-1.0 | 1.7 | 2.2 |
| 1.1-3.0 | 0.9 | 1.8 |
| 3.1-10.0 | 0 | 2.0 |
| 10.1-20.0 | 0 | 6.9 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 3.4 | 13.7 |
| TOTAL *(kg/m$^2$)* | *(0.76)* | *(3.07)* |

## UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 951 ft$^3$/ac *(66.5 m$^3$/ha)*

Percent sound 0 %

Percent rotten 100 %

Avg. diameter:

sound -- in

Sound & rotten 8.9 in *(22.6 cm)*

## POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 0.6 | 0.4 | 0.3 |
| | 10 | 9 | 5 | 3 |
| | 20 | 16 | 8 | 5 |
| Perimeter Growth rate (ch/h) | 0 | 3 | 2 | 1 |
| | 10 | 24 | 12 | 7 |
| | 20 | 24 | 12 | 7 |
| Burned area After 1 h (acres) | 0 | 0.05 | 0.02 | 0.01 |
| | 10 | 3 | 1 | 0.3 |
| | 20 | 3 | 1 | 0.3 |
| Head fire Flame length (feet) | 0 | 1 | 1 | 1 |
| | 10 | 4 | 3 | 3 |
| | 20 | 5 | 4 | 3 |
| Crown scorch By head fire (feet) | 0 | 4 | 3 | 2 |
| | 10 | 7 | 5 | 3 |
| | 20 | 5 | 3 | 2 |
| Head fire Intensity (Btu/ft/s) | 0 | 7 | 5 | 4 |
| | 10 | 105 | 74 | 54 |
| | 20 | 188 | 113 | 78 |

## PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 2800 (Avg. d.b.h. <1") |
| Stems remaining per acre | 426 |
| Average d.b.h. before (inches) | 1 |
| Average d.b.h. after (inches) | 4 |
| Basal area/acre before | 54 |
| Basal area/acre after | 39 |
| Thinning method | Chainsaw |
| Slash treatment | None |

## OTHER INFORMATION

Slash age 4 months

Average slope 20 percent

Species composition: WC 95%, GF 5%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 10

2-WC-1-TH

## DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 1.3 | 1.3 |
| 0.25-1.0 | 2.5 | 2.5 |
| 1.1-3.0 | 1.5 | 1.5 |
| 3.1-10.0 | 0 | 1.6 |
| 10.1-20.0 | 0 | 0 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 5.3 | 6.9 |
| TOTAL *(kg/m$^2$)* | *(1.19)* | *(1.55)* |

## UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 171 ft$^3$/ac *(12.0 m$^3$/ha)*

Percent sound 100 %

Percent rotten 0 %

Avg. diameter:

sound 3.9 in *(9.9 cm)*

Sound & rotten 3.9 in *(9.9 cm)*

## PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 4300 (Avg. d.b.h. <1") |
| Stems remaining per acre | 426 |
| Average d.b.h. before (inches) | 1 |
| Average d.b.h. after (inches) | 4 |
| Basal area/acre before | 62 |
| Basal area/acre after | 39 |
| Thinning method | Chainsaw |
| Slash treatment | None |

## OTHER INFORMATION

Slash age 4 months

Average slope 10 percent

Species composition: WC 70%, GF 30%

## POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 1 | 0.5 | 0.3 |
| | 10 | 15 | 8 | 5 |
| | 20 | 28 | 12 | 7 |
| Perimeter Growth rate (ch/h) | 0 | 4 | 2 | 1 |
| | 10 | 39 | 19 | 11 |
| | 20 | 53 | 19 | 11 |
| Burned area After 1 h (acres) | 0 | 0.1 | 0.03 | 0.02 |
| | 10 | 8 | 2 | 0.6 |
| | 20 | 8 | 2 | 0.6 |
| Head fire Flame length (feet) | 0 | 2 | 1 | 1 |
| | 10 | 5 | 4 | 3 |
| | 20 | 7 | 5 | 4 |
| Crown scorch By head fire (feet) | 0 | 6 | 3 | 3 |
| | 10 | 15 | 7 | 5 |
| | 20 | 12 | 4 | 3 |
| Head fire Intensity (Btu/ft/s) | 0 | 13 | 6 | 5 |
| | 10 | 215 | 100 | 77 |
| | 20 | 396 | 160 | 115 |

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 16

3-WC-1-TH

## DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 1.5 | 1.5 |
| 0.25-1.0 | 3.5 | 4.3 |
| 1.1-3.0 | 4.4 | 5.7 |
| 3.1-10.0 | 1.2 | 8.8 |
| 10.1-20.0 | 0 | 32.8 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 10.6 | 53.1 |
| TOTAL *(kg/m²)* | *(2.38)* | *(11.90)* |

## UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 4296 ft³/ac *(300.6 m³/ha)*

Percent sound 16 %

Percent rotten 84 %

Avg. diameter:

sound 4.4 in *(1.2 cm)*

Sound & rotten 8.0 in *(20.3 cm)*

## POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 1 | 0.8 | 0.5 |
| | 10 | 17 | 10 | 6 |
| | 20 | 30 | 16 | 9 |
| Perimeter Growth rate (ch/h) | 0 | 5 | 3 | 2 |
| | 10 | 45 | 27 | 17 |
| | 20 | 70 | 33 | 18 |
| Burned area After 1 h (acres) | 0 | 0.2 | 0.1 | 0.04 |
| | 10 | 10 | 4 | 1 |
| | 20 | 10 | 4 | 1 |
| Head fire Flame length (feet) | 0 | 2 | 2 | 2 |
| | 10 | 7 | 7 | 6 |
| | 20 | 10 | 8 | 7 |
| Crown scorch By head fire (feet) | 0 | 10 | 9 | 7 |
| | 10 | 32 | 25 | 17 |
| | 20 | 25 | 16 | 10 |
| Head fire Intensity (Btu/ft/s) | 0 | 30 | 25 | 19 |
| | 10 | 438 | 350 | 248 |
| | 20 | 772 | 523 | 347 |

## PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 2552(Avg. d.b.h. 2") |
| Stems remaining per acre | 491 |
| Average d.b.h. before (inches) | 2 |
| Average d.b.h. after (inches) | 5 |
| Basal area/acre before | 133 |
| Basal area/acre after | 77 |
| Thinning method | Chainsaw |
| Slash treatment | None |

## OTHER INFORMATION

Slash age 3 months

Average slope 0 percent

Species composition: WC 75%, GF 25%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 39

## DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) | |
|---|---|---|
| | Slash Only | Total Debris |
| 0-0.25 | 1.3 | 1.3 |
| 0.25-1.0 | 3.9 | 4.6 |
| 1.1-3.0 | 6.3 | 6.9 |
| 3.1-10.0 | 0 | 6.1 |
| 10.1-20.0 | 0 | 0 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 11.5 | 18.9 |
| TOTAL *(kg/m$^2$)* | *(2.58)* | *(4.24)* |

## UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 652 ft$^3$/ac *(45.6 m$^3$/ha)*

Percent sound 0 %

Percent rotten 100 %

Avg. diameter:

sound -- in

Sound & rotten 8.3 in *(21.1 cm)*

## POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 1 | 0.8 | 0.5 |
| | 10 | 21 | 12 | 7 |
| | 20 | 36 | 17 | 9 |
| Perimeter Growth rate (ch/h) | 0 | 6 | 3 | 2 |
| | 10 | 53 | 31 | 18 |
| | 20 | 82 | 36 | 18 |
| Burned area After 1 h (acres) | 0 | 0.3 | 0.1 | 0.03 |
| | 10 | 14 | 5 | 2 |
| | 20 | 14 | 5 | 2 |
| Head fire Flame length (feet) | 0 | 2 | 2 | 2 |
| | 10 | 8 | 7 | 6 |
| | 20 | 11 | 9 | 7 |
| Crown scorch By head fire (feet) | 0 | 11 | 9 | 7 |
| | 10 | 41 | 30 | 19 |
| | 20 | 33 | 19 | 10 |
| Head fire Intensity (Btu/ft/s) | 0 | 37 | 38 | 19 |
| | 10 | 574 | 422 | 263 |
| | 20 | 990 | 614 | 360 |

## PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 2701(Avg. d.b.h. 2") |
| Stems remaining per acre | 426 |
| Average d.b.h. before (inches) | 2 |
| Average d.b.h. after (inches) | 4 |
| Basal area/acre before | 98 |
| Basal area/acre after | 39 |
| Thinning method | Chainsaw |
| Slash treatment | None |

## OTHER INFORMATION

Slash age 3 months

Average slope 10 percent

Species composition: WC 90%, GF 10%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 40

5-WC-1-TH

### DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 1.9 | 1.9 |
| 0.25-1.0 | 3.6 | 4.7 |
| 1.1-3.0 | 5.1 | 5.4 |
| 3.1-10.0 | 1.8 | 8.4 |
| 10.1-20.0 | 0 | 1.0 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 12.4 | 21.4 |
| TOTAL *(kg/m²)* | *(2.78)* | *(4.80)* |

### UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 889 ft³/ac *(62.2 m³/ha)*

Percent sound 46 %

Percent rotten 54 %

Avg. diameter:

sound 4.0 in *(10.2 cm)*

Sound & rotten 4.7 in *(11.9 cm)*

### POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 1 | 1 | 0.5 |
| | 10 | 16 | 10 | 6 |
| | 20 | 25 | 15 | 9 |
| Perimeter Growth rate (ch/h) | 0 | 5 | 3 | 2 |
| | 10 | 41 | 25 | 16 |
| | 20 | 65 | 34 | 19 |
| Burned area After 1 h (acres) | 0 | 0.2 | 0.1 | 0.04 |
| | 10 | 8 | 3 | 1 |
| | 20 | 8 | 3 | 1 |
| Head fire Flame length (feet) | 0 | 2 | 2 | 2 |
| | 10 | 7 | 7 | 6 |
| | 20 | 10 | 8 | 7 |
| Crown scorch By head fire (feet) | 0 | 10 | 9 | 8 |
| | 10 | 32 | 25 | 19 |
| | 20 | 25 | 16 | 11 |
| Head fire Intensity (Btu/ft/s) | 0 | 32 | 27 | 23 |
| | 10 | 442 | 350 | 265 |
| | 20 | 789 | 532 | 376 |

### PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 2850 (Avg. d.b.h. 2") |
| Stems remaining per acre | 491 |
| Average d.b.h. before (inches) | 2 |
| Average d.b.h. after (inches) | 5 |
| Basal area/acre before | 139 |
| Basal area/acre after | 77 |
| Thinning method | Chainsaw |
| Slash treatment | None |

### OTHER INFORMATION

Slash age 3 months

Average slope 10 percent

Species composition: WC 55%, GF 23%, WWP 22%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 39

6. WC-1-TH

CODE:

### DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 4.7 | 4.7 |
| 0.25-1.0 | 4.1 | 4.1 |
| 1.1-3.0 | 6.8 | 6.8 |
| 3.1-10.0 | 11.8 | 16.2 |
| 10.1-20.0 | 0 | 7.2 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 27.4 | 39.0 |
| TOTAL (*kg/m²*) | (*6.14*) | (*8.74*) |

### UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 2181 ft³/ac (*152.6 m³/ha*)

Percent sound 51 %

Percent rotten 49 %

Avg. diameter:

sound 3.7 in (*9.4 cm*)

Sound & rotten 4.5 in (*11.4 cm*)

### POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 3 | 1 | 1 |
| | 10 | 42 | 16 | 10 |
| | 20 | 79 | 27 | 16 |
| Perimeter Growth rate (ch/h) | 0 | 11 | 5 | 3 |
| | 10 | 108 | 42 | 27 |
| | 20 | 180 | 62 | 37 |
| Burned area After 1 h (acres) | 0 | 1 | 0.2 | 0.1 |
| | 10 | 58 | 9 | 4 |
| | 20 | 64 | 9 | 4 |
| Head fire Flame length (feet) | 0 | 4 | 2 | 2 |
| | 10 | 15 | 8 | 7 |
| | 20 | 19 | 10 | 8 |
| Crown scorch By head fire (feet) | 0 | 25 | 10 | 9 |
| | 10 | 124 | 35 | 25 |
| | 20 | 129 | 26 | 17 |
| Head fire Intensity (Btu/ft/s) | 0 | 122 | 33 | 26 |
| | 10 | 1903 | 482 | 354 |
| | 20 | 3586 | 803 | 552 |

### PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 3240(Avg. d.b.h. 3") |
| Stems remaining per acre | 491 |
| Average d.b.h. before (inches) | 3 |
| Average d.b.h. after (inches) | 5 |
| Basal area/acre before | 236 |
| Basal area/acre after | 77 |
| Thinning method | Chainsaw |
| Slash treatment | None |

### OTHER INFORMATION

Slash age 2 months

Average slope 0 percent

Species composition: WC 50%, GF 50%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 60

7-WC-1-TH

## DEBRIS LOADING

| Size Class (inches) | Weight (tons/acre) Slash Only | Weight (tons/acre) Total Debris |
|---|---|---|
| 0-0.25 | 6.0 | 6.0 |
| 0.25-1.0 | 5.9 | 6.4 |
| 1.1-3.0 | 11.4 | 13.9 |
| 3.1-10.0 | 16.3 | 23.0 |
| 10.1-20.0 | 2.6 | 11.3 |
| 20.1+ | 0 | 0 |
| TOTAL tons/acre | 42.2 | 60.6 |
| TOTAL *(kg/m²)* | *(9.5)* | *(13.6)* |

## UTILIZATION POTENTIAL OF DEBRIS LARGER THAN 3-INCH DIAMETER

Volume 3136 ft$^3$/ac *(219.4 m$^3$/ha)*

Percent sound 57 %

Percent rotten 43 %

Avg. diameter:

sound 4.4 in *(11.2 cm)*

Sound & rotten 5.0 in *(12.7 cm)*

## POTENTIAL FIRE BEHAVIOR ASSESSMENT

| Quantity Assessed | Wind mi/h | Slash Age In No. Of Winters 1 | 3 | 5 |
|---|---|---|---|---|
| Head fire Spread rate (ch/h) | 0 | 2 | 1 | 1 |
| | 10 | 28 | 14 | 9 |
| | 20 | 52 | 23 | 14 |
| Perimeter Growth rate (ch/h) | 0 | 10 | 5 | 4 |
| | 10 | 72 | 36 | 24 |
| | 20 | 118 | 52 | 315 |
| Burned area After 1 h (acres) | 0 | 1 | 0.2 | 0.1 |
| | 10 | 26 | 6 | 3 |
| | 20 | 27 | 6 | 3 |
| Head fire Flame length (feet) | 0 | 4 | 3 | 3 |
| | 10 | 14 | 10 | 9 |
| | 20 | 19 | 13 | 11 |
| Crown scorch By head fire (feet) | 0 | 27 | 18 | 16 |
| | 10 | 117 | 60 | 47 |
| | 20 | 118 | 47 | 32 |
| Head fire Intensity (Btu/ft/s) | 0 | 143 | 75 | 65 |
| | 10 | 1780 | 850 | 653 |
| | 20 | 3283 | 1367 | 980 |

## PRECOMMERCIAL THINNING INFORMATION

| | |
|---|---|
| Stems cut/acre | 4146 (Avg. d.b.h. 3") |
| Stems remaining per acre | 491 |
| Average d.b.h. before (inches) | 3 |
| Average d.b.h. after (inches) | 5 |
| Basal area/acre before | 280 |
| Basal area/acre after | 77 |
| Thinning method | Chainsaw |
| Slash treatment | None |

## OTHER INFORMATION

Slash age 4 months

Average slope 0 percent

Species composition: GF 60%, WC 30%, DF 5%, WWP 5%

IDAHO FOREST PRACTICE ACT
SLASH HAZARD POINTS

FUEL QUANTITY 60

ki, Wayne H., and William C. Fischer.
979. Photo series for appraising thinning slash in north Idaho: western hemlock, grand fir, and western redcedar timber types. USDA For. Serv. Gen. Tech. Rep. INT-46, 50 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Three series of color photographs show different levels of down woody material re- ing from precommercial thinning operations in three north Idaho timber types. h photo is supplemented by inventory data describing the size, weight, and volume he debris pictured. Stand data relating to the thinning operation are provided and mates of predicted fire behavior and Idaho Forest Practice Act slash hazard rating given.

YWORDS: slash, forest fuels, thinning, fire behavior, fire hazard

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YWORDS: slash, forest fuels, thinning, fire behavior, fire hazard

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# Measuring cross sections using a sag tape: A generalized procedure

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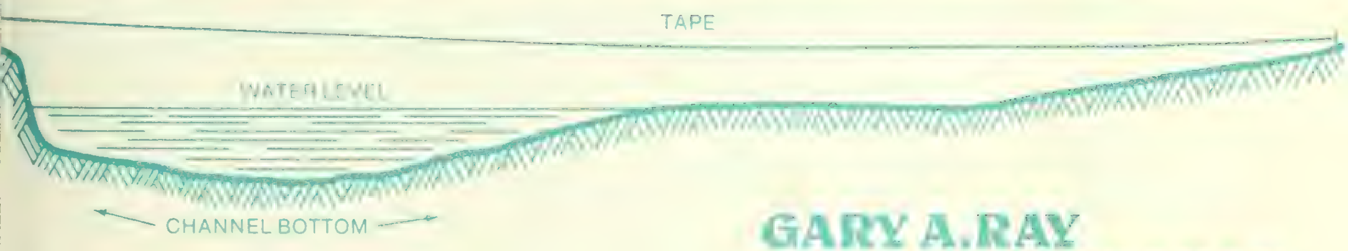

GARY A. RAY
WALTER F. MEGAHAN

USDA Forest Service General Technical Report INT-47
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE

USDA Forest Service
General Technical Report INT-47
January 1979

# Measuring cross sections using a sag tape:
## A generalized procedure

GARY A. RAY
WALTER F. MEGAHAN

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

# THE AUTHORS

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WALTER F. MEGAHAN is Principal Research Hydrologist and Leader of the Intermountain Station's Idaho Batholith Ecosystems research work unit in Boise, Idaho. He holds bachelor's and master's degrees in Forestry from the State University of New York, College of Forestry at Syracuse University, and a doctoral degree in Watershed Resources from Colorado State University. He served as Regional Hydrologist for the Intermountain Region of the Forest Service in Ogden, Utah, from 1960 to 1966 and has been in his present position since 1967.

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# RESEARCH SUMMARY

A procedure was developed for surveying cross sections using a sag tape with unequal end elevations. Information needed to perform the necessary calculations includes: the tape weight (lb) per foot of length; the difference in elevation (ft) between the two ends of the tape; the tension (lb) on the tape; and the tape length (ft). The procedure is as accurate as traditional engineer's level surveys and is faster and easier. Examples of a typical field survey and the resulting cross section plot are provided. The procedure is easily programed for a digital computer; a flow diagram for calculating and plotting cross sections is provided.

# INTRODUCTION

Hydrologists, geologists, and civil engineers commonly use cross section surveys nsisting of a series of paired horizontal and vertical measurements to describe the ape, or changes in shape, of the earth's surface. Usually, cross section surveys e made by measuring horizontal distances along a tape stretched between two refer- ce stakes and by measuring vertical distances with an engineer's level and a level d. Although this technique can be fairly accurate, it is time consuming, requires o people, and has a relatively large possibility for observer error.

A simpler procedure is to measure vertical distances with a level rod directly om the tape to the point of interest on the underlying surface. However, this pro- dure requires that a correction be made to account for the inevitable sag in the tape. e calculation is relatively simple if both ends of the tape are at the same elevation that the low point of the tape is located in the center of the cross section. Com- ter programs to calculate (DEBRIS) and plot (PLOT D) cross sections taken with a sag pe with equal end tape elevations are presently available (USDA Forest Service, Water- ed Systems Development Unit 1975). The programs were originally designed to evaluate diment accumulations in debris basins where it is relatively easy to set the ends of e measuring tape at the same elevation. Unfortunately, it has been our experience at the programs have limited application because it is usually difficult and often possible to establish the ends of the tape at the same elevation.

To solve this problem, we have developed a procedure which permits the use of the g tape for any combination of end elevations. This procedure can be used in a much der variety of applications than the previous method. For example, hydrologists can e it for documenting channel bank erosion and bottom aggradation and degradation; for aluating aquatic habitat conditions; for establishing water surface profiles; and for termining the amount of erosion and deposition on hill slopes and construction areas.

# CALCULATION OF SAG CORRECTION

A tape, suspended between two end points, describes a catenary curve. If the end ints of the tape are at the same elevation and if the weight per foot of the tape is own and the tension in the tape is measured, it is easy to calculate the shape of the tenary curve according to the equation given by Thomas (1960). Once this shape is own, you can make the necessary corrections in vertical distance and you can correct stances measured along the tape to true horizontal distances thereby adding to the curacy of the survey.

Marks (1951) provides a method for the solution of a catenary curve with unequal d elevations. Unfortunately, the procedure given is inadequate for two reasons: (1) assumes that the true x coordinate distance between the ends of the tape (the value

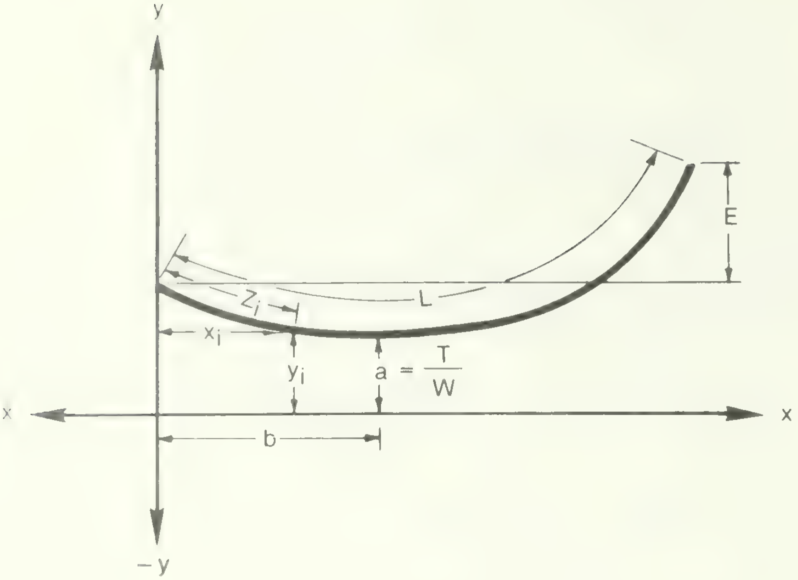


*Figure 1.--Dimensions required to calculate the shape of a catenary curve with unequal end elevations.*

c in our appendix derivation) is known; and (2) the formulae required to derive the tables are not given, thereby making the procedure impossible to accurately implement. In practical application, the true x coordinate distance between the ends of the tape is unknown, and formulae must be available for efficient solution on a computer.

In order to describe the catenary curve defined by a tape suspended between two points of unequal elevation, it is necessary to locate the x coordinate of the low point of the curve (defined as b, fig. 1). This is possible if the tape length (L) in feet, the tape tension (T) in pounds, the tape weight per unit length (W) in pounds pe foot, and the elevations of the tape ends in feet are known. The elevation of the rig tape end minus the elevation of the left tape end defines the value of E in the following calculations.

The value of b is computed as follows:

$$b = a \ln\left[\{(L-E)/a\}\{1/(1-1/K)\}\right]$$

where:

$$a = T/W$$

$$K = \{-H+(H^2-4)^{0.5}\}/2.$$

$$H = -\{(L^2-E^2)/a^2\}-2.$$

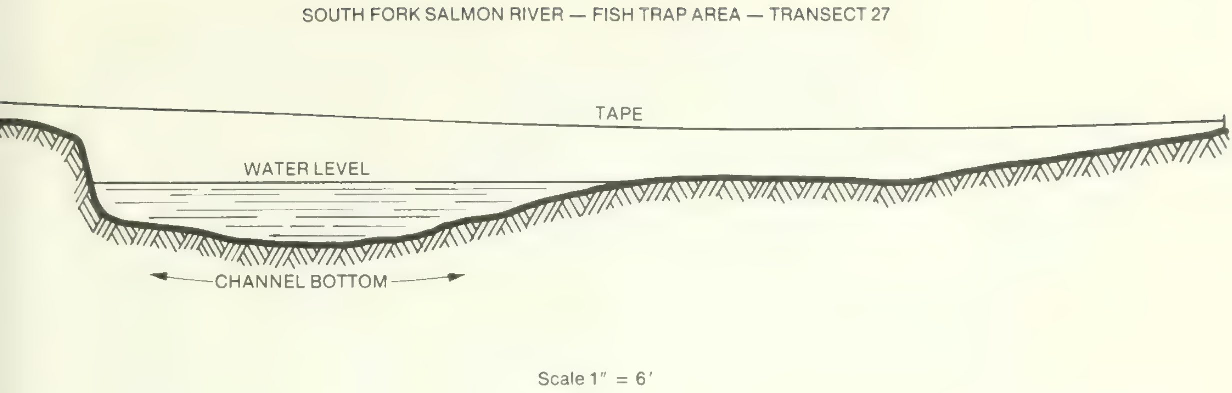
When b is known, the x coordinate of any point on the catenary ($x_i$) can be calculated for a given tape distance $z_i$ with the following:

$$x_i = a \sinh^{-1}\left(\frac{z_i}{a} + \sinh\frac{-b}{a}\right) + b$$

and the accompanying y coordinate ($y_i$) calculated as:

$$y_i = a \cosh\{(x_i-b)/a\}.$$

Derivations of these equations are given in appendix 1.



*gure 2.--Example of an actual stream channel cross section plot using the sag tape procedure, showing the channel bottom and the water level.*

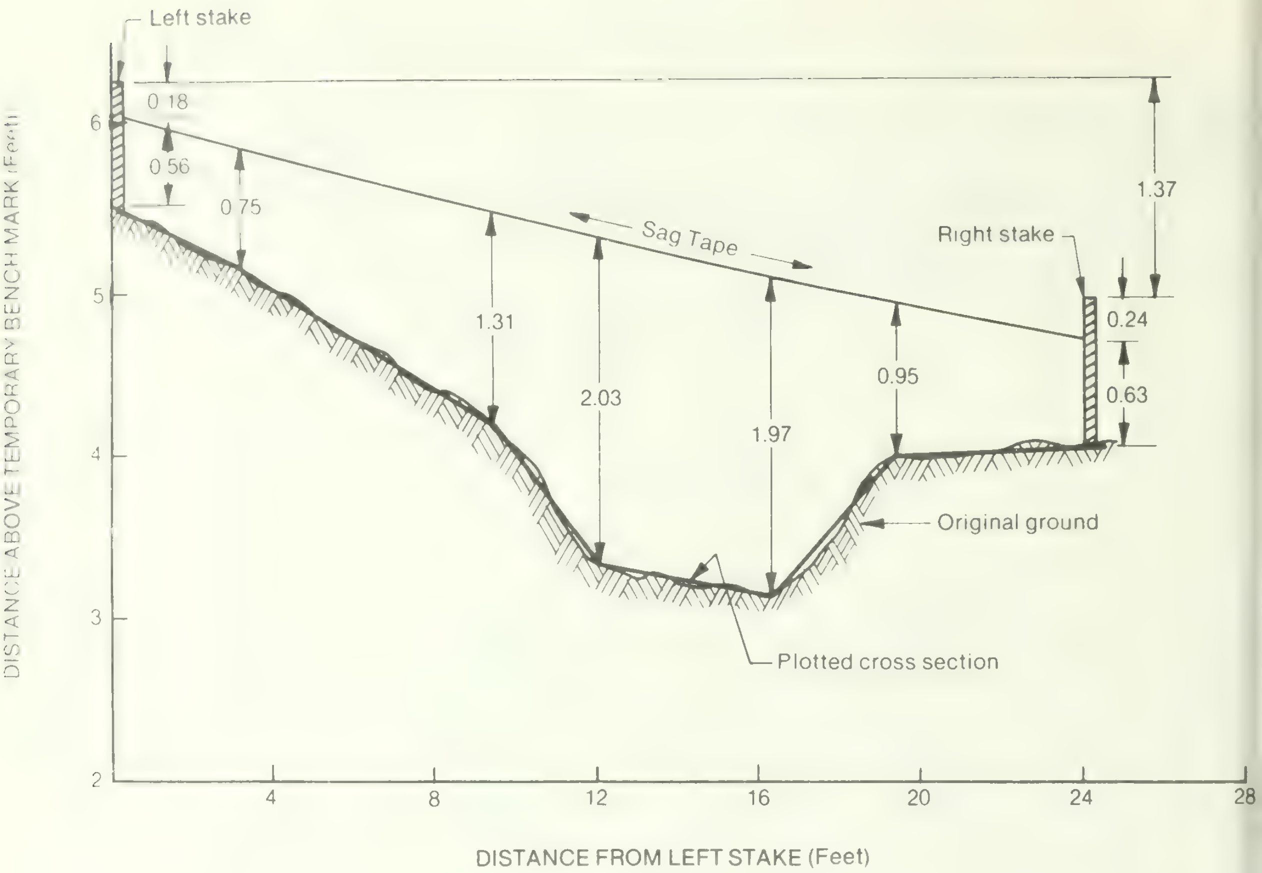
For very precise surveys, corrections can be made in the above equation to account r tape stretch, heat expansion, and the additional tension provided by the weight of e tape. Such corrections are not warranted for most field applications. Interested aders should refer to standard references (e.g., Marks 1951) to apply these corrections.

When the x and y coordinates of the tape for any tape reading are known, the y ordinate of the surface being surveyed is obtained by subtracting the measured ver- cal distance between the tape and the surface being surveyed from the y coordinate the tape.

The above calculations are easily programed for computer analysis. We have veloped a program for a Hewlett Packard 9821A programable calculator equipped with 3 registers that provides a plot of the cross section and the survey tape (fig. 2). flow chart for the program is given in appendix 2. Additional field data collected the time of the cross section survey can also be incorporated into the cross section alysis. For example, water depth data collected while surveying channel cross ctions make it possible to plot the water level in figure 2.

# FIELD PROCEDURES

Stable end stakes must be installed at the ends of each cross section prior to king a cross section survey. Many times, it is necessary to remeasure cross sec- ions periodically to document changes over time. In this case, end stakes should installed permanently to insure stability. An accurate survey is required to tablish the difference in elevation between the two end stakes. An engineer's vel and level rod are suggested for this purpose. Once the relative elevations of e stakes are known, no additional surveys are needed unless there is suspicion at the stakes may have moved.



Field Notes

Date 6/12/77, Location South fork Salmon River
Cross Section No. 24, Observer(s) L. Jones
Tape wgt./ft. 0.012714 (lb/ft) Tape Tension 16.5 (lb)
Elevation[1] right top of stake 4.98 (ft.)
Elevation left top of stake 6.35 (ft.)
Top right stake to tape 0.24 (ft.)
Top left stake to tape 0.18 (ft.)

| Tape distance | Vertical |
|---|---|
| 0.0 | 0.56 |
| 3.2 | 0.75 |
| 9.5 | 1.31 |
| 12.1 | 2.03 |
| 16.3 | 1.97 |
| 19.3 | 0.95 |
| 24.2 | 0.63 |

---

[1] Based on a temporary bench mark elevation of 10.00 feet.

Figure 3.--Example of field notes and the resulting cross section plot.

The actual cross section survey requires a steel tape, a spring scale graduated up to about 30 pounds, a tape clamp, and a level rod. All equipment can be obtained from survey equipment suppliers. The zero end of the tape is attached to the left[1] end stake and the tape is stretched to the right end stake where it is attached to the spring scale with the use of a tape clamp. Care must be taken to assure that the tape is not touching anything for its entire length. Tension of at least 5 pounds plus 1 pound for each 10 feet in length is applied to the tape. Tape tension should be increased when conditions are windy. Excessive tape sway may make it necessary to delay field operations when using long tape spans (>100 feet) under high wind conditions (>15-20 miles per hour), especially when winds are blowing normal to the tape.

Paired tape and vertical distances are measured to the desired precision along the tape, including the points of attachment of each end of the tape, in order to locate the tape with respect to the surface being surveyed. Measurements are taken as necessary in order to define the shape of the cross section. Straight lines are assumed between measurement points on the surface being surveyed, so it is desirable to take readings at all major breaks in slope along the cross section. The distance from the top of each stake to the end of the tape must be measured in order to reference the height of the ends of the tape. An example of field notes for a cross section survey and of the resulting cross section plot is shown in figure 3.

Calculations from the survey data are as follows:

$L$ = length of tape = 24.2 ft

$E$ = elevation of right end of tape minus elevation of left end of tape
$= (4.98 - 0.24) - (6.35 - 0.18)$
$= -1.43$ ft

$a$ = tension/tape weight per ft
= 16.5 lb/0.012714 lb/ft
= 1297.78197300 ft

$$H = -\{(24.2^2 - (-1.43)^2)/a^2\} - 2$$
$$= -2.00034650$$

$$K = (-H + \sqrt{H^2-4})/2 = 1.01878867$$

$$b = a \ln \left[\{(24.2 + 1.43)/a\}\{1/(1 - 1/K)\}\right]$$
$$= 88.85524249.$$

The x and y coordinates of the tape and the ground surface are calculated as in the following examples:

At $z_1 = 0$, $x_1 = 0$,

$$y_1 = a \cosh \left(\frac{-b}{a}\right) = 1300.82,$$

ground surface $= y_1 - 0.56 = 1300.26$.

---

[1] The convention of whether to define right and left by looking upstream or downstream is the surveyor's choice; use should be consistant once the choice is made.

At $L_6 = 12.1$, $x_6 = a \sinh^{-1}(\frac{12.1}{a} + \sinh\frac{-b}{a}) + b = 12.08$,

$y_6 = a \cosh(\frac{12.08-b}{a}) = 1300.05$,

ground surface = $y_6 - 2.03 = 1298.02$.

At $L_7 = 24.2$, $x_7 = a \sinh^{-1}(\frac{24.2}{a}) + \sinh\frac{-b}{a}) + b = 24.16$,

$y_7 = a \cosh(\frac{24.16-b}{a}) = 1299.39$,

ground surface = $y_7 - 0.63 = 1298.76$.

Some peculiarities of the calculations require explanation. First, the values a, H, K, and b must be carried to at least 8 significant digits to assure precise calculation of the tape coordinates. Also, the value for a is calculated by dividing the tape tension by the tape weight per foot of length. A large number results (a = 1297.78197300 ft in the example) because the tape tension is large compared to the tape weight per foot of length. The value a is actually the distance between the low point of the tape and an imaginary horizontal coordinate plane (see fig. 1). All other positions on the tape (the calculated values for $y_i$) are referenced to the same coordinate plane and are likewise large. A constant can be added or subtracted from the computed values for $y_i$ to reference the values to any other coordinate plane. For example, a constant of 1294.65 was subtracted from the $y_i$ values computed above in order to reference the values used to plot the cross section in figure 3 to the 10.00 foot bench mark used for the field survey. The constant was determined by subtracting the elevation of the left end of the tape based on the temporary bench mark (6.17) from the computed value of $y_i$ for the left end of the tape (1300.82).

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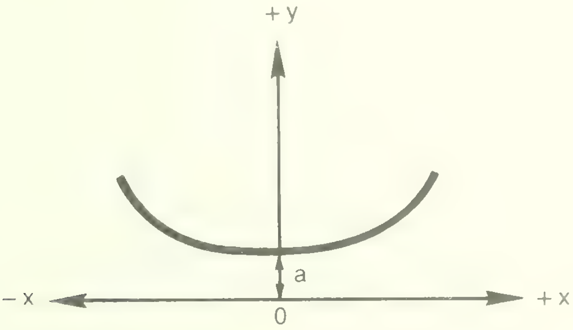
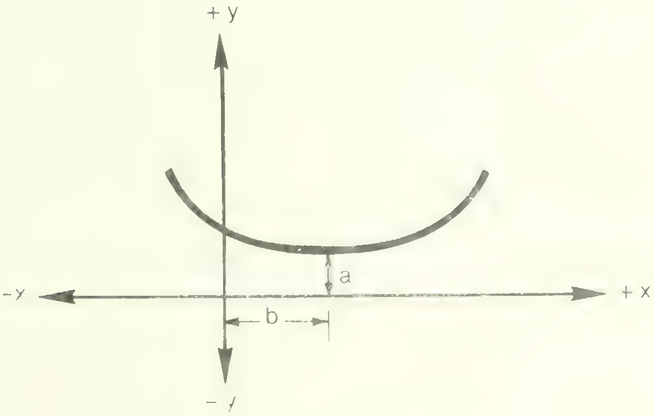
# APPENDIX 1

Derivation of equations for calculating the position of a sag tape with unequal end elevations

The equation of a catenary (hanging chain) is $y = a \cosh \frac{x}{a}$ where a is tension weight per unit length, and the low point is at $x = 0$ (Thomas 1960).

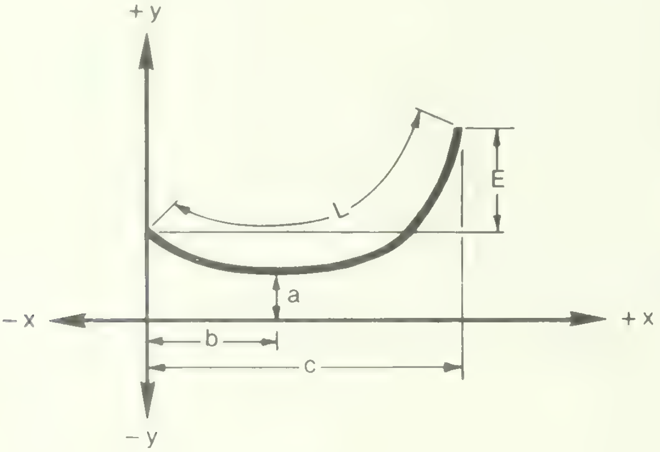


A more general equation, where the low point is at $x = b$, is $y = a \cosh \frac{x-b}{a}$.



Let one stake be at x = 0, the other stake at x = c. Let the length of the tape between the two stakes be L, and the difference in the height of the stakes be E. The problem now is: given a, E, and L, find b.

$$f(x) = a \cosh \frac{x-b}{a}$$



L is the arc length from 0 to c, so

$$L = \int_0^c \sqrt{1 + (f'(x))^2}\, dx = \int_0^c \sqrt{1 + \sinh^2 \frac{x-b}{a}}\, dx$$

$$= \int_0^c \cosh \frac{x-b}{a}\, dx = a \sinh \frac{c-b}{a} - a \sinh \frac{-b}{a}$$

so,

$$\sinh \frac{c-b}{a} - \sinh \frac{-b}{a} = \frac{L}{a} \; . \qquad (1)$$

Solving for f(x) at 0 and c,

$$E^{2/} = a \cosh \frac{c-b}{a} - a \cosh \frac{-b}{a}$$

so,

$$\cosh \frac{c-b}{a} - \cosh \frac{-b}{a} = \frac{E}{a} \; . \qquad (2)$$

---

[2] In this derivation, E is defined as the elevation of the *right* end of tape (f(x) at c) minus the elevation of the *left* end of the tape (f(x) at 0).

Using the definitions of cosh (x) and sinh (x) with $\frac{c-b}{a} = p$, $\frac{-b}{a} = q$, equations (1) and (2) become:

$$\frac{e^p - e^{-p}}{2} - \frac{e^q - e^{-q}}{2} = \frac{L}{a} \tag{3}$$

and,
$$\frac{e^p + e^{-p}}{2} - \frac{e^q + e^{-q}}{2} = \frac{E}{a} . \tag{4}$$

Adding (3) and (4),

$$e^p - e^q = \frac{L + E}{a}.$$

Subtracting (4) from (3),

$$-e^{-p} + e^{-q} = \frac{L - E}{a}$$

so,
$$e^{\frac{c}{a} - \frac{b}{a}} - e^{-\frac{b}{a}} = \frac{L + E}{a}$$

$$-e^{-\frac{c}{a} + \frac{b}{a}} + e^{\frac{b}{a}} = \frac{L - E}{a}$$

or,
$$-e^{-\frac{b}{a}} \left[ e^{\frac{c}{a}} - 1 \right] = \frac{L + E}{a}$$

$$e^{\frac{b}{a}} \left[ -e^{-\frac{c}{a}} + 1 \right] = \frac{L - E}{a} \tag{5}$$

so,
$$-e^{-\frac{b}{a}} = \frac{a}{L - E} \left[ -e^{-\frac{c}{a}} + 1 \right]. \tag{6}$$

Substituting (6) into (5) gives:

$$\left[ -e^{-\frac{c}{a}} + 1 \right] \left[ e^{\frac{c}{a}} - 1 \right] = \frac{L^2 - E^2}{a^2}$$

or,
$$e^{\frac{c}{a}} + e^{-\frac{c}{a}} - 2 = \frac{L^2 - E^2}{a^2} .$$

Multiplying both sides by $e^{\frac{c}{a}}$ gives:

$$\left[e^{\frac{c}{a}}\right]^2 + \left(-\frac{L^2 - E^2}{a^2} - 2\right)\left(e^{\frac{c}{a}}\right) + 1 = 0. \tag{7}$$

Let $K = e^{\frac{c}{a}}$ and $H = -\frac{L^2 - E^2}{a^2} - 2$ and (7) becomes:

$$K^2 + HK + 1 = 0$$

so,

$$K = \frac{-H \pm \sqrt{H^2 - 4}}{2}. \tag{8}$$

From this,

$$c = a \ln K. \tag{9}$$

Also from (6),

$$e^{\frac{b}{a}} = \frac{a}{L - E}\left[-1/K + 1\right]$$

and, $$e^{\frac{b}{a}} = \frac{L - E}{a}\left[\frac{1}{1 - 1/K}\right]$$

so, $$b^{1} = a \ln\left[\frac{L - E}{a}\left(\frac{1}{1 - 1/K}\right)\right].$$

From (8), K can have two possible values; however, in any real situation,

$$K = \frac{-H + \sqrt{H^2 - 4}}{2}. \tag{10}$$

This is because c > 0, so K > 1 by (9). And because $K^2 + HK + 1 = 0$, the two possible values of K are reciprocals; hence, the larger must be chosen in order for c to be > 0.

---

[1] The value b may be negative. Negative values result when the low point of the curve is located to the left of the coordinate origin.

In order to change from distances along the tape to true horizontal distances, let $z_i$ be the distance along the tape from $x = 0$, and let $x_i$ be the distance along the x axis.

$$z_i = \int_0^{x_i} \sqrt{1 + \sinh^2 \frac{x_i - b}{a}}\, dx_i$$

$$= a \sinh \frac{x_i - b}{a} - a \sinh \frac{-b}{a}$$

so, $$\sinh \frac{x_i - b}{a} = \frac{z_i}{a} + \sinh \frac{-b}{a}$$

$$\frac{x_i - b}{a} = \sinh^{-1}\left(\frac{z_i}{a} + \sinh \frac{-b}{a}\right).$$

The accompanying y coordinate ($y_i$) is

$$y_i = a \cosh \left(\frac{x_i - b}{a}\right).$$

The coordinates of the surface being surveyed are:

$x_i$

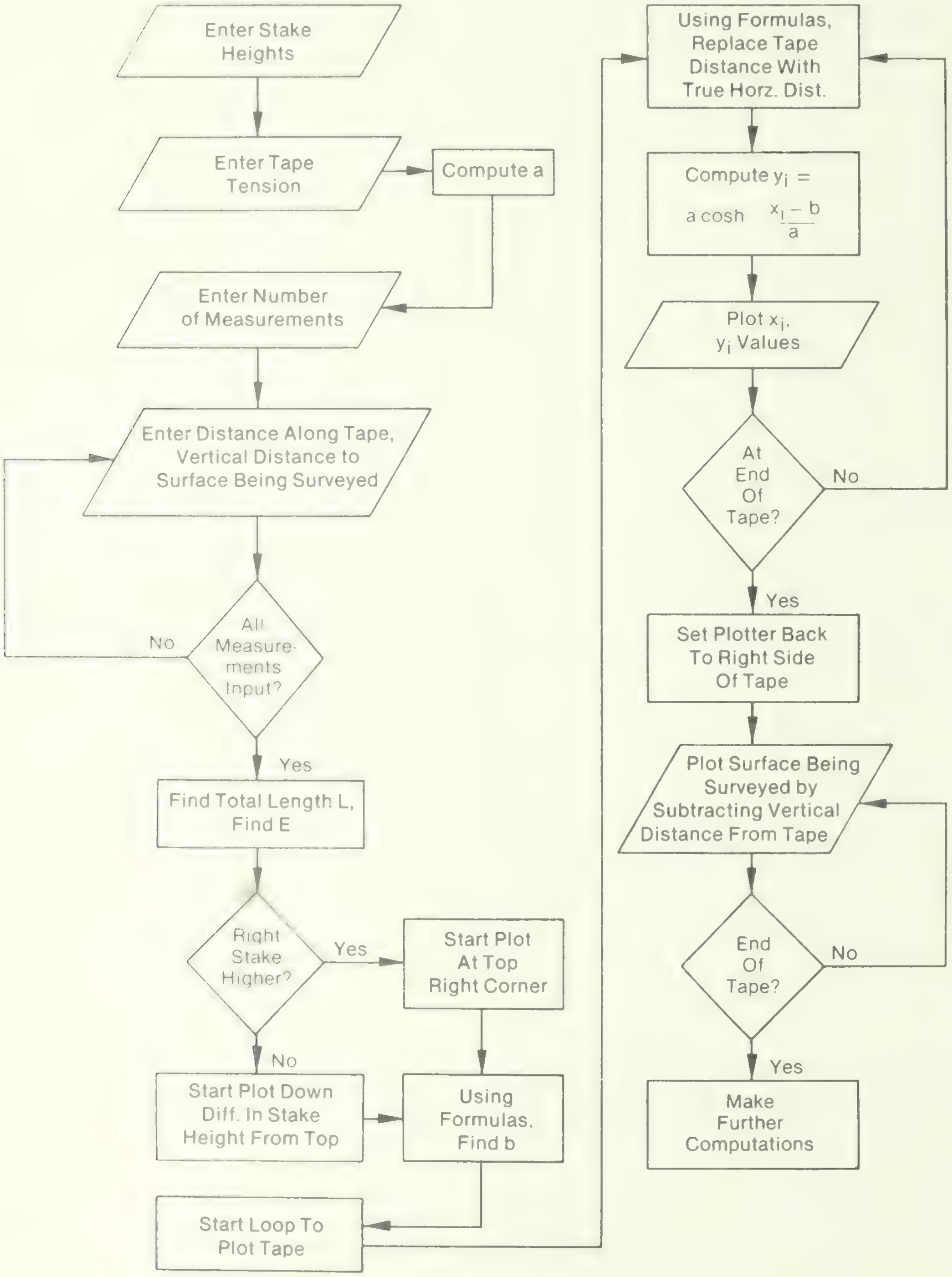
and

$y_i - d_i$

where $d_i$ = the vertical distance from the tape to the surface.

## APPENDIX 2

Flow chart for calculating and plotting cross sections taken with a sag tape


Enter Stake Heights
Enter Tape Tension
Compute a
Enter Number of Measurements
Enter Distance Along Tape, Vertical Distance to Surface Being Surveyed
All Measurements Input?
No
Yes
Find Total Length L, Find E
Right Stake Higher?
Yes
No
Start Plot At Top Right Corner
Start Plot Down Diff. In Stake Height From Top
Using Formulas, Find b
Start Loop To Plot Tape
Using Formulas, Replace Tape Distance With True Horz. Dist.
Compute $y_i = a \cosh \frac{x_i - b}{a}$
Plot $x_i$, $y_i$ Values
At End Of Tape?
No
Yes
Set Plotter Back To Right Side Of Tape
Plot Surface Being Surveyed by Subtracting Vertical Distance From Tape
End Of Tape?
No
Yes
Make Further Computations

☆U S GOVERNMENT PRINTING OFFICE 1979-0-677-019/45

Ray, Gary A., and Walter F. Megahan.
1979. Measuring cross sections using a sag tape: a generalized procedure. USDA For. Serv. Gen. Tech. Rep. INT-47, 12 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

A procedure was developed for surveying cross sections using a sag tape with unequal end elevations. The procedure is as accurate as traditional engineer's level surveys, is faster and easier, and can be programed for a digital computer by following the flow diagram which is provided.

KEYWORDS: survey, cross sections, streambank erosion, channel degradation, channel aggradation, aquatic habitat, water profiles, erosion, deposition, profiles.

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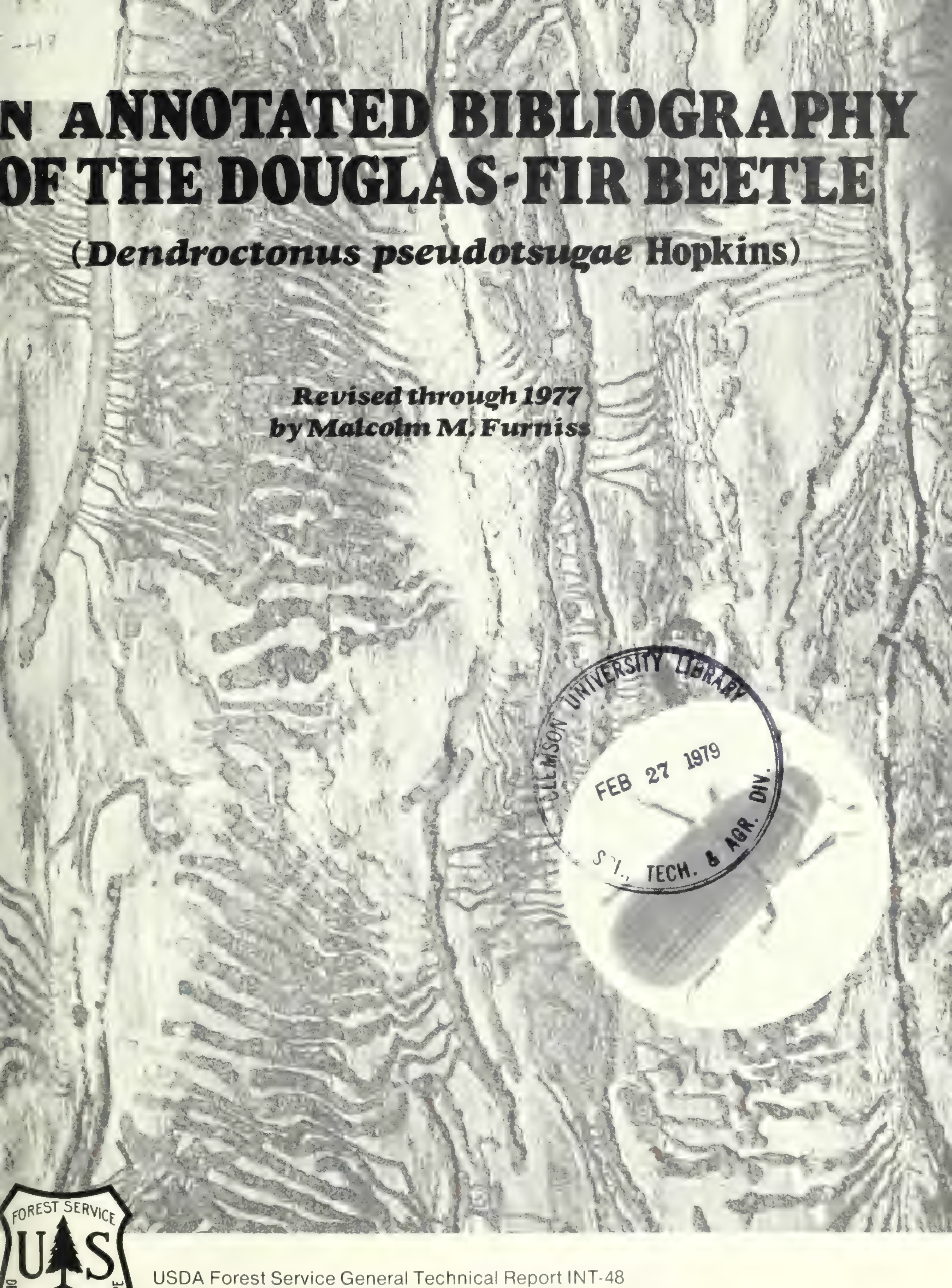

# N ANNOTATED BIBLIOGRAPHY OF THE DOUGLAS-FIR BEETLE

## (*Dendroctonus pseudotsugae* Hopkins)

***Revised through 1977***
***by Malcolm M. Furniss***

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USDA Forest Service General Technical Report INT-48
INTERMOUNTAIN FOREST & RANGE EXPERIMENT STATION
Ogden, Utah 84401

## THE AUTHOR

MALCOLM M. FURNISS stationed at the Forestry Sciences Laboratory, Moscow, Idaho, leads a research unit dealing with the insects of conifers and shrubs. He has studied insects on shrubs in relation to big game ranges since 1961 and has for a longer time studied ecology of bark beetles in forest trees. He has published extensively on their ecological relationships, bionomics, and pheromones.

## ABSTRACT

Annotates contents of 263 published references of the Douglas-fir bark beetle through 1977. Includes only publications of major importance directly related to the Douglas-fir beetle. References are indexed by author and subject. Updates USDA Forest Service General Technical Report INT-8, 1973.

USDA Forest Service
General Technical Report INT-48
February 1979

# AN ANNOTATED BIBLIOGRAPHY OF THE DOUGLAS-FIR BEETLE

**(*Dendroctonus pseudotsugae* Hopkins)**

**Compiled by
Malcolm M. Furniss**

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

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# FOREWORD

The Douglas-fir beetle (Dendroctonus pseudotsugae Hopkins) is one of the more destructive western bark beetles. Outbreaks commonly occur in mature unmanaged stands after trees are damaged by weather (windthrown or topbroken by snow) or sometimes by fire or defoliators. Infestations may persist for several years in interior stands, aided by drought, root disease, and other predisposing factors.

This bibliography updates through 1977 a similar work by Furniss and Oakes (1973). Citations that are new to the 1973 edition are denoted by an asterisk. References are indexed by author and subject. Generally, only published articles are included; thus, these and most reports are omitted. Also omitted are references concerning insects that may occur with the Douglas-fir beetle if those references did not deal significantly with the Douglas-fir beetle. For example, if a publication mentions a predator of the Douglas-fir beetle in relation to another species of bark beetle, that publication would not be included here. Neither have I listed publications that I considered to be of minor importance, nor those that appear in essence in references included in this bibliography.

# BIBLIOGRAPHY

1. ANONYMOUS. 1971. Douglure: a powerful tool in manipulating the Douglas-fir beetle. South. For. Res. Inst. Prog. Rep., May-June, 1971:11-12.

In Idaho, 147 live trees were baited with a mixture of frontalin, camphene, and α-pinene. By late June, these trees, and 480 nearby, had been attacked by beetles.

2. ALLEN, DONALD G., ROBERT R. MICHAEL, and SOLON A. STONE. 1958. Sounds of Douglas-fir beetle activity. Oreg. For. Lands Res. Cent., Corvallis, Res. Note 36, 19 p.

Behavior of beetles in their natural habitat was inferred from their sounds. Stridulation and boring activities were monitored with sound-amplifying and recording equipment. Characteristics of these sounds were analyzed by using an oscilloscope.

3. ALLEN, D. G., and J. A. RUDINSKY. 1959. Effectiveness of Thiodan, Sevin, and lindane on insects attacking freshly cut Douglas-fir logs. J. Econ. Entomol. 52:482-484.

Douglas-fir beetle attacks were unsuccessful on all logs treated with 3 pounds of active ingredient to 100 gallons of water 19 weeks after treatment, except Sevin-treated logs had 0.1 successful attack per $ft^2$. Treatments using 1 lb per 100 gal of water were less protective.

4. ATKINS, M. D. 1957. A study of the effect of nematodes and mites on Douglas-fir beetle flight. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 13(5):2-3.

Infestation by nematodes and mites had no effect on flight response and duration.

5. ATKINS, M. D. 1959. A method for the close-up photography of insect behavior. Can. Entomol. 91:328-329.

The Douglas-fir beetle was used to demonstrate how insect behavior may be studied photographically if a few basic reactions of an insect are known (e.g., the beetles' tendency to walk up an incline toward light and into a flow of air before preparing to fly).

6. ATKINS, M. D. 1959. A study of the flight of the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopk. (Coleoptera: Scolytidae). I. Flight-preparation and response. Can. Entomol. 91:283-291.

Infestation of beetles by mites and nematodes did not affect the beetles' flight behavior; however, light intensity and temperature did. Females, but not all males, lost their ability or inclination to fly after start of gallery construction.

7. ATKINS, M. D. 1960. A study of the flight of the Douglas-fir beetle *Dendroctonus pseudotsugae* Hopk. (Coleoptera: Scolytidae). II. Flight movements. Can. Entomol 92:941-954.

Wing-beat amplitude and frequency were characterized and studied in relation to infestation by mites and nematodes, temperature, humidity, light, atmospheric pressure, and fatigue.

8. ATKINS, M. D. 1961. A study of the flight of the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopk. (Coleoptera: Scolytidae). III. Flight capacity. Can. Entomol 93:467-474.

Describes study of duration, and to a lesser extent, velocity, in relation to presence of mites and nematodes, physical factors, and history of beetle (i.e., spring-emerged vs. re-emerged). Velocities on flight mills were compared to those in free flight.

9. ATKINS, M. D. 1966. Behavioural variation among scolytids in relation to their habitat. Can. Entomol. 98:285-288.

A philosophical thesis correlating various behavior to temporary habitat; the Douglas-fir beetle is cited incidentally.

10. ATKINS, M. D. 1966. Laboratory studies on the behaviour of the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins. Can. Entomol. 98:953-991.

Exhaustive study of the relationships between beetle response to physical factors and their subsequent response to host logs. Response to host varied with fat content; those having less fat were host-positive, others were host-negative.

11. ATKINS, M. D. 1966. Studies on the fat content of the Douglas-fir beetle. Can. Dep. For. Bimon. Res. Notes 22(4):3.

Highest fat content was found in beetles that (a) had not flown, (b) had develope under cool conditions, and (c) were not crowded during development.

12. ATKINS, MICHAEL D. 1967. The effect of rearing temperature on the size and fat content of the Douglas-fir beetle. Can. Entomol. 99:181-187.

Temperature influenced rate of development, brood size, and fat content. Fat content of adults declined during the overwintering period. Suggests that amount of chan in fat content depends upon the duration of activity periods, diapause, and the feedin and metabolism rates. Because these processes are controlled by temperature, the prediction of population quality and behavior requires a thorough understanding of the effects of weather differences on bark beetle broods.

13. ATKINS, M. D. 1968. Scolytid pheromones--ready or not. Can. Entomol. 100:1115-1117.

Discusses the built-in dangers of using bark-beetle pheromones without conclusive knowledge of the biology, behavior, and genetics of the species to be managed.

14. ATKINS, MICHAEL D. 1969. Lipid loss with flight in the Douglas-fir beetle. Can Entomol. 101:164-165.

Beetles flown on flight mills showed considerable fat loss when compared to simil beetles from an unflown control group.

15. ATKINS, M. D. 1975. On factors affecting the size, fat content, and behavior of a scolytid. Z. Angew. Entomol. 78:209-218.

Average dry weight and extractable fat of larvae and new adults decreased with ncreasing gallery density (2, 8, 12/ft$^2$). Reared at 13°C, larvae, pupae, and new dults weighed more and contained more fat at gallery densities of 2/ft$^2$ rather than 2/ft$^2$; the reverse was true at 21°C. Fat contents of young adults decreased between amples taken 60, 90, and 120 days after gallery initiation, more so at constant temerature of 21°C than at fluctuating temperatures. Responsiveness of beetles to olfacory stimuli is affected by fat content.

6. ATKINS, M. D., and J. A. CHAPMAN. 1957. Studies on nervous system anatomy of the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopk. (Scolytidae). Can. Entomol. 89:80-86.

Describes the main anatomical features of the adult beetle nervous system. Unusual eatures include variation in origination and branching of abdominal nerve trunks and he rather posterior position of the frontal ganglion relative to the brain.

7. ATKINS, M. D., and S. H. FARRIS. 1958. A technique for measuring flight muscle changes in the Douglas-fir beetle, *Dendroctonus pseudotsugae*. Can. Dep. Agric., For. Biol. Div. Sci. Serv. Bimon. Prog. Rep. 14(4):3-4.

Presents procedures for preparing serial sections of flight muscles to measure hanges during degeneration and regeneration.

8. ATKINS, M. D., and S. H. FARRIS. 1962. A contribution to the knowledge of flight muscle changes in the Scolytidae (Coleoptera). Can. Entomol. 94:25-32.

Flight muscles of male and female Douglas-fir beetles degenerated during either rood establishment or starvation. Females' muscles degenerated about 15 days sooner han the males' muscles. Conditions correlated with degeneration included narrowing nd displacement of muscle bundles, loss of evident striations, and intrusion of fat odies into the muscle area. The space and substance of their flight muscles, or both, ay be utilized during periods when flight dispersal is not required.

9. ATKINS, M. D., and L. H. McMULLEN. 1958. Selection of host material by the Douglas-fir beetle. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 14(1):3.

Beetles attacked log sections lying on the ground much more intensely than secions set upright. Authors speculate that this could be attributed to (a) easier anding and (b) differences in heating by the sun.

0. ATKINS, MICHAEL DONALD, and L. H. McMULLEN. 1960. On certain factors influencing Douglas-fir beetle populations. Fifth World For. Congr. Proc., Seattle, Wash., 2:857-859.

Illustrates how beetle populations are affected by weather, preference for certain ost material, and resulting competition.

21. BAKER, BRUCE H., BRUCE B. HOSTETLER, and MALCOLM M. FURNISS. 1977. Response of eastern larch beetle (Coleoptera:Scolytidae) in Alaska to its natural attractant and to Douglas-fir beetle pheromones. Can. Entomol. 109:289-294.

Larch beetles were attracted to seudenol + α-pinene or logs containing 20 unmated emale Douglas-fir beetles; attraction was repressed by MCH. Neither frontalin nor *rans*-verbenol was attractive. Predacious *Thanasimus* spp. were scarce, although they ave been caught abundantly by frontalin elsewhere.

*22. BAKER, B. H., and G. C. TROSTLE. 1973. Douglas-fir beetle attraction and tree-group response. J. Econ. Entomol. 66:1002-1005.

Capsules of frontalin and camphene were placed on 157 trees 4 chains apart, causing all baited trees to become infested. Live trees within 33 ft of baited trees, or check trees, were infested at a rate of 58.5% and 3.6%, respectively. Larger trees and those closest to baited trees were attacked most frequently.

23. BEDARD, W. D. 1933. The number of larval instars and the approximate length of the larval stadia of *Dendroctonus pseudotsugae* Hopk., with a method for their determination in relation to other bark beetles. J. Econ. Entomol. 26:1128-1134.

First and second instar larvae were reared on inner bark between two glass plates. When Dyar's law was applied to their head width measurements, it indicated [erroneously] five instars. Duration of stadia was determined using Taylor's method.

24. BEDARD, WILLIAM DELLES. 1937. Biology and control of the Douglas-fir beetle *Dendroctonus pseudotsugae* Hopkins (Coleoptera-Scolytidae) with notes on associated insects. Wash. State Coll. Res. Stud. 5:103-105. (Abstr.)

Ph.D. dissertation on biology, natural enemies, and associates. Parasites and predators accounted for 89.2% brood mortality, mainly in the egg and larval stages.

25. BEDARD, W. D. 1938. An annotated list of the insect fauna of Douglas-fir (*Pseudotsuga mocronata* Rafinesque) in the northern Rocky Mountain region. Can. Entomol. 70:188-197.

Lists 153 insect species associated with the tree. Brief annotations refer to habitat, relationships to the beetle, and seasonal history.

26. BEDARD, W. D. 1950. The Douglas-fir beetle. U.S. Dep. Agric. Circ. 817, 10 p.

Describes biology, seasonal history, infestation characteristics, ecological relationships, and control. [Needs updating.]

27. BELLUSCHI, P. G., and NORMAN E. JOHNSON. 1969. The rate of crown fade of trees killed by the Douglas-fir beetle in southwestern Oregon. J. For. 67:30-32.

Yearly weather patterns determined the rate of crown fade of beetle-killed Douglas-fir. In a wet and cool year, one-fourth to one-third of the trees had faded by fall; in a dry year, two-thirds were faded.

28. BELLUSCHI, P. G., NORMAN E. JOHNSON, and H. J. HEIKKENEN. 1965. Douglas-fir defects caused by the Douglas-fir beetle. J. For. 63:252-256.

Many attacked trees survive but the unsuccessful egg galleries are grown over and become defects that affect product quality.

29. BENNETT, ROY B., and JOHN H. BORDEN. 1971. Flight arrestment of tethered *Dendroctonus pseudotsugae* and *Trypodendron lineatum* (Coleoptera: Scolytidae) in response to olfactory stimuli. Ann. Entomol. Soc. Am. 64:1273-1286.

Tethered male Douglas-fir beetles stopped flying in response to odors of female frass. Response occurred only after previous flight exercise. Females did not respond to frass, but both males and females were arrested by phloem odors. Before flight,

---

[1] Comments in brackets are those of the author of the bibliography.

beetles swallowed air, which may be a pressure-sensory mechanism related to observation that beetles flew well only on clear days.

*30. BORDEN, JOHN H. 1968. Sex pheromone of *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae): production bio-assay, and partial isolation. Can. Entomol. 100: 597-603.

Response of beetles to frass, frass extracts, and distillates was determined with an olfactometer employing a light source at right angle to an air stream. Frass collected 2 h after females were introduced into logs was attractive to males; peak attractiveness occurred at 8 h and declined thereafter. Virgin females removed from galleries after 2 weeks produced attractive frass when reintroduced into logs. Distilled filtrate of benzene extract of frass was exponentially attractive over a range of $2.3 \times 10^{-4}$ to $10^{-1}$. The attractant was eluted from a silica gel column with a mixture of benzene and ether. Response to combinations of fractions indicated a 3-way synergism.

*31. BORDEN, JOHN H. 1974. Aggregation pheromones in the Scolytidae. *In* Birch, M. C. (ed.), Pheromones, p. 135-160. North-Holland Publishing Co., Amsterdam, 495 p.

Examples include Douglas-fir beetle orientation to host, cessation of flight, and pheromone production including predator response.

*32. BORDEN, JOHN H. 1977. Behavioral responses of Coleoptera to pheromones, allomones, and kairomones. *In* Shorey, H. H., and J. J. McKelvey, Jr. (eds.), Chemical control of insect behavior: theory and application, p. 169-198. John Wiley & Sons, New York.

Examples involving *D. pseudotsugae* and its coleopterous predators are interspersed in this review of literature.

33. BORDEN, JOHN H., and R. B. BENNETT. 1969. A continuously recording flight mill for investigating the effect of volatile substances on the flight of tethered insects. J. Econ. Entomol. 62:782-785.

Describes operation of a rotary flight mill and photocell-ratemeter-paperchart recorder. Flying male Douglas-fir beetles ceased flight abruptly when sex pheromone (female frass) was introduced into the flight chamber.

34. BORDEN, JOHN H., and M. McCLAREN. 1970. Biology of *Cryptoporus volvatus* (Peck) Shear (Agaricales, Polyporaceae) in southwestern British Columbia: distribution, host species, and relationship with subcortical insects. Syesis 3:145-154.

During the year after trees are attacked by Douglas-fir beetles, *C. volvatus* hyphae extrude through holes made by the beetles and develop sporophores. Circumstantially, the predator *Temnochila virescens* var. *chlorodia* (Mann.) is suggested as a likely vector.

35. BORDEN, JOHN H., R. M. SILVERSTEIN, and R. G. BROWNLEE. 1968. Sex pheromone of *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae): production, bio-assay, and partial isolation. Can. Entomol. 100:597-603.

Attractiveness of frass increased up to 8 h after attack, then declined but was substantially renewed when females reemerged and attacked again. Extracts and distillates of frass were attractive; response increased greatly with increased concentration. Response to combinations of fractions indicated a three-way synergism but the most attractive component was contained in one fraction.

*36. BORDEN, J. H., K. N. SLESSOR, and K. MORI. 1976. *Gnathotrichus sulcatus*: synergistic response to enantiomers of the aggregation pheromone sulcatol. Science 192:894-896.

Authors mention in introduction that the Douglas-fir beetle is more sensitive to R-(-)- than to S-(+)- frontalin.

*37. BORDEN, J. H., T. J. VANDER SAR, and E. STOKKINK. 1975. Secondary attraction in the Scolytidae: an annotated bibliography. Simon Fraser Univ., Dep. Biol. Sci., Pest Manage. Pap. 4, 97 p.

Includes 46 annotated references dealing with secondary attraction of the Douglas-fir beetle.

*38. BRAND, J. M., J. W. BRACKE, A. J. MARKOVETZ, D. L. WOOD, and L. E. BROWNE. 1975. Production of verbenol pheromone by a bacterium isolated from bark beetles. Nature (Lond.) 254:136-137.

A filamentous yeast phase fungus, SJB-133, from mycangia of female *Dendroctonus frontalis* converted seudenol (3-methyl-2-cyclohexen-1-ol) to MCH (3-methyl-2-cyclohexen-1-one). The authors speculate that termination of attraction of Douglas-fir beetles in host trees may come about by conversion of seudenol to MCH by microorganisms.

*39. BRIGHT, DONALD E., JR. 1976. The insects and arachnids of Canada. Part 2. The bark beetles of Canada and Alaska. Coleoptera:Scolytidae. Can. Dep. Agric. Publ. 1576, 241 p.

Summarizes adult features, hosts, distribution in British Columbia and Alberta, and biology. [States erroneously that progeny of spring attack emerge that year.]

*40. BRIGHT, D. E., JR., and R. W. STARK. 1973. The bark and ambrosia beetles of California. Coleoptera:Scolytidae and Platypodidae. Bull. Calif. Insect Surv., Vol. 16, 169 p. Univ. Calif. Press, Berkeley.

Contains couplet to *D. pseudotsugae* in key to species, distribution map, and summary of biology. [Biology identical to Bright (1976) including erroneous statement about progeny of spring attacks emerging that year.]

41. BUSHING, RICHARD W. 1965. A synoptic list of the parasites of Scolytidae (Coleoptera) in North America north of Mexico. Can. Entomol. 97:449-492.

Hymenopterous parasites of the Douglas-fir beetle include species of *Coeloides*, *Campoplex*, *Cecidostiba*, *Cheiropachus*, *Tomicobia* [misidentification, see Furniss, M. M., 1968, p. 1338] and *Roptrocerus*. Also discusses briefly various scolytid parasites in regard to their morphology, seasonal history, host-tree selection, parasitism, importation and colonization, and the importance of controlling their beetle hosts.

*42. CASTELLO, JOHN D., CHARLES GARDNER SHAW, and M. M. FURNISS. 1976. Isolation of *Cryptoporus volvatus* and *Fomes pinicola* from *Dendroctonus pseudotsugae*. Phytopathology 66:1431-1434.

*Cryptoporus volvatus* (Pk.) Hubbard and *Fomes pinicola* (Swartz ex. Fr.) were isolated from Douglas-fir beetles trapped in flight. Mycelial fragments are the likely propagules. Evidence indicates that the beetle is a major vector of *C. volvatus*, a common cause of sapwood rot in beetle-killed trees.

43. CHAMBERLIN, W. J. 1918. Bark-beetles infesting the Douglas-fir. Oreg. Agric. Exp. Stn. Bull. 147, 40 p.

Illustrates unidentified parasite [*Coeloides brunneri*]; lists the following mites s possible predators: *Seius safroi* Ewing, *Bdella magna* Ewing, and a species of Gamasidae. Other predators mentioned are *Clerus sphegens* Fabr. [*Enoclerus sphegeus*], *icndella longilabris* Say, *Dasyllis posticata* Say, and *Dasyllis* sp.?. [Technically outated but of historical value.]

4. CHAMBERLIN, W. J. 1939. The bark and timber beetles of North America. Oreg. State Coll. Coop. Assoc., Corvallis. 513 p.

Mites claimed to be associated with Douglas-fir beetle (p. 67-68) include *Pedicuoides ventricosus*, *Seius safroi* Ewing, and *Bdella magna* Ewing (in mines).

5. CHAMBERLIN, W. J. 1958. The Scolytoidea of the Northwest. Oregon, Washington, Idaho, and British Columbia. Oreg. State Coll., Corvallis, Oreg. State Monogr. 2, 208 p.

Briefly discusses aspects of the beetle, including habits, seasonal history, and iology.

6. CHANSLER, JOHN F. 1968. Douglas-fir beetle brood densities and infestation trends on a New Mexico study area. USDA For. Serv. Res. Note RM-125, 4 p.

During 1959-64, average numbers of adult beetles just prior to flight (May) ppeared to be correlated with numbers of trees attacked after emergence. Variance in rood numbers between trees was greater at 5 ft than at 10 ft aboveground.

7. CHANSLER, JOHN F., and DONALD A. PIERCE. 1966. Bark beetle mortality in trees injected with cacodylic acid (herbicide). J. Econ. Entomol. 59:1357-1359.

Douglas-fir beetle broods were reduced 87% by injecting trees with cacodylic acid hortly after attack.

8. CHAPMAN, J. A. 1954. Flight of *Dendroctonus pseudotsugae* in the laboratory. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 10(4):4.

Beetles attached to rotating mills flew continuously up to 9 h at velocities of 0-40 meters per min. Additional flights occurred.

9. CHAPMAN, J. A. 1955. Ingestion of paper and vegetables by the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopk. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 11(2):4.

Callow beetles were fed various paper substances, fruits, and vegetables to deterine the nutritional value of the materials. A portion of each material was ingested ut amounts varied among the beetles. The amount consumed was never as great as normal eeding in bark.

0. CHAPMAN, J. A. 1955. Sex determination by stridulation sounds in the Douglas-fir beetle, *Dendroctonus pseudotsugae*. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 11(3):2.

Sexing of live beetles by sound of male stridulation was done rapidly and did not arm them. When combined with feeling the roughness of the elytral declivity this ethod was almost 100 percent accurate, even with callow adults.

1. CHAPMAN, J. A. 1963. Field selection of different log odors by scolytid beetles. Can. Entomol. 95:673-676.

Scolytid beetles responded to four different log odors released from test boxes. *Dendroctonus pseudotsugae* was attracted only to Douglas-fir odors.

52. CHAPMAN, J. A. 1966. The effect of attack by the ambrosia beetle *Trypodendron lineatum* (Olivier) on log attractiveness. Can. Entomol. 98:50-59.

Douglas-fir beetles did not respond to "secondary attraction" from *Trypodendron* boring in the test logs.

53. CHAPMAN, J. A. 1967. Response behaviour of scolytid beetles and odour meteorology. Can. Entomol. 99:1132-1137.

Suggests that transport and dispersal of odors by air currents is an important factor in scolytid response to attractant sources. Knowledge of odor meteorology would increase effectiveness of attractants and repellents in scolytid control.

54. CHAPMAN, J. A., and E. D. A. DYER. 1969. Cross attraction between the Douglas-fir beetle [*Dendroctonus pseudotsugae* Hopk.] and the spruce beetle [*D. obesus* (Mann.)]. Can. Dep. Fish. and For., For. Serv., Bimon. Res. Notes 25(4):31.

Field populations of flying Douglas-fir beetles or spruce beetles responded similarly to females of either beetle species in either white spruce or Douglas-fir.

55. CHAPMAN, JOHN A., and JAMES M. KINGHORN. 1955. Window flight traps for insects. Can. Entomol. 87:46-47.

Glass barrier traps were used to sample flying populations of scolytids. Douglas-fir beetle was the fourth most numerous scolytid species caught.

56. CHAPMAN, J. A., and J. M. KINGHORN. 1958. Studies of flight and attack activity of the ambrosia beetle, *Trypodendron lineatum* (Oliv.), and other scolytids. Can. Entomol. 90:326-372.

Douglas-fir beetles showed the greatest flight and attack activity during May.

57. CHAPMAN, J. A., and J. W. WILSON. 1956. The use of impregnated paper as an approach to nutritional studies with the Douglas-fir beetle. J. Econ. Entomol. 49:426-427.

Seven carbohydrates were added to chemically-defined papers to study food requirements of adult beetles. Conclusions regarding carbohydrate preference were difficult because the beetles did not readily ingest the papers.

*58. CIESLA, W. M., M. M. FURNISS, M. D. McGREGOR, and W. E. BOUSFIELD. 1971. Evaluation of Douglas-fir beetle infestations in the North Fork Clearwater River drainage, Idaho--1971. USDA For. Serv., North. Reg., Insect and Dis. Rep. 71-46, 15 p.

During 1970-71 beetles killed 85.8 million bd. ft. of Douglas-fir. The outbreak wa associated with extensive cutting of trees for a reservoir and trees broken by ice and snow. Mortality was estimated by two-stage sampling with 1:7920 scale aerial photos (Ektachrome infrared aero type 8443) and 100-acre ground plots. Beetle attacks were unsuccessful in 31% of the trees. Brood/parent ratio in successfully-attacked trees was 1.2 and 86% of the brood were callow adults in early fall.

59. CORNELIUS, ROYCE O. 1955. How forest pests upset management plans in the Douglas-fir region. J. For. 53:711-713.

The Douglas-fir beetle killed 3.5 billion bd. ft. of timber in Oregon during 1950-1954. As a result of the dead timber, management development plans were disrupted, allowable cut was exceeded, and fire hazard was increased.

60. COWAN, B. D., and W. P. NAGEL. 1965. Predators of the Douglas-fir beetle in western Oregon. Oreg. State Univ., Agric. Exp. Stn. Tech. Bull. 86, 32 p.

Of six clerids studied, *Enoclerus sphegeus* Fab. was most prevalent and effective against the Douglas-fir beetle. Three species (*Thanasimus undatulus* Say, *E. lecontei* Wolcott, and *Enoclerus* sp.) were questionably associated with the Douglas-fir beetle; two species (*E. schaefferi* and *E. eximus*) were not. Considerable information is given on life history and abundance of *E. sphegeus*; less information is given for the other species.

*61. DEYRUP, MARK A. 1975. The insect community of dead and dying Douglas-fir. I. The Hymenoptera. Univ. Wash., Seattle, Coniferous For. Biome Ecosystem Anal. Stud. Bull. 6, 104 p.

Among 70+ spp. of Hymenoptera associated with dying or dead Douglas-fir, some such as *Coeloides brunneri* parasitize *D. pseudotsugae*. Included are excellent illustrations, keys to families, genera and species, and discussion of biology and ecology where known.

*62. DOLPH, R. E., JR., C. SARTWELL, R. L. JOHNSEY, L. N. KLINE, P. G. LAUTERBACH, and G. STEVENS. 1975. Insects. *In* Forest residues management guidelines for the Pacific Northwest, p. 151-152, 168-169, 198-200. USDA For. Serv. Gen. Tech. Rep. PNW-33, 273 p.

Recommends disposing of infested green stem residue >8-inch diameter or moving it at least 35 ft from live Douglas-fir. Shaded stem residue in selection cut areas is of highest priority for treatment. Fresh windthrow and fire-injured trees should be removed within 12 months.

63. DYER, E. D. A., and J. A. CHAPMAN. 1965. Flight and attack of the ambrosia beetle, *Trypodendron lineatum* (Oliv.) in relation to felling date of logs. Can. Entomol. 97:42-57.

Among logs felled over a 10-month period, Douglas-fir beetles responded strongest to those felled during late winter and early spring.

64. DYER, E. D. A., J. P. SKOVSGAARD, and L. H. McMULLEN. 1968. Temperature in relation to development rates of two bark beetles. Can. Dep. For. & Rural Dev., For. Br., Bimon. Res. Notes 24(2):15-16.

Douglas-fir beetle brood developed fastest at the highest of four constant temperatures (62°, 52°, 49°, 43°F). Its threshold temperature for development (43 to 49°F) was higher than that of the spruce beetle.

65. EVENDEN, JAMES C., and KENNETH H. WRIGHT. 1955. Douglas-fir beetle. USDA For. Serv., For. Pest Leafl. 5, 4 p.

Gives general information on the Douglas-fir beetle, including some control methods. [Superseded by Furniss and Orr 1970.]

66. FANG, S. C., and DON ALLEN. 1955. Distribution and incorporation of radioactive phosphorus in the Douglas-fir beetle. J. Econ. Entomol. 48:79-82.

Beetles were fed radioactive phosphorus after which the percent radioactivity of five parts of the body was determined. Presents the relative amounts of $P_{32}$ contained by compounds; carbohydrates had most, fat had little.

67. FARRIS, S. H. 1965. A preliminary study of mycangia in the bark beetles, *Dendroctonus ponderosae* Hopk., *Dendroctonus obesus* Mann., and *Dendroctonus pseudotsugae* Hopk. Can. Dep. For., For. Entomol. and Pathol. Br., Bimon. Prog. Rep. 21(5):3-4.

Only 1 of 25 teneral adult female Douglas-fir beetles had fungoid material, which was in the coxal cavities and integumental folds of the scutellum.

68. FITZGERALD, T. D., and W. P. NAGEL. 1970. Preemergence orientation of *Medetera aldrichii* (Diptera: Dolichopodidae). Ann. Entomol. Soc. Am. 63:913-914.

Prior to pupation, larvae of *Medetera aldrichii* aggregate near openings to the outer bark. Laboratory tests indicated that light entering the openings was the cause of larval aggregation. Formation of pupae cells near openings facilitates the subsequent migration of photopositive pupae to the bark surface where adults eclose.

69. FITZGERALD, T. D., and W. P. NAGEL. 1972. Oviposition and larval bark-surface orientation of *Medetera aldrichii* (Diptera: Dolichopodidae): Response to a prey liberated plant terpene. Ann. Entomol. Soc. Am. 65:328-330.

Female *Medetera aldrichii* laid eggs near Douglas-fir beetle entrances and ventilation holes. Emanation of a volatile compound, such as D-alpha-pinene, from prey galleries may stimulate oviposition and guide newly eclosed predator larvae toward pre gallery openings.

70. FURNISS, MALCOLM M. 1959. Reducing Douglas-fir beetle damage-how it can be done USDA For. Serv., Intermt. For. and Range Exp. Stn. Res. Note 70, 6 p.

Brief discussion of biology, infestation characteristics, and recommendations for preventing or lessening damage.

71. FURNISS, M. M. 1962. A circular punch for cutting samples of bark infested with beetles. Can. Entomol. 94:959-963.

Describes construction and operation of a 1/10-ft$^2$ circular punch used to sample Douglas-fir beetle populations. Discusses advantages of the punch and compares its efficiency to that of larger sampling units.

72. FURNISS, MALCOLM M. 1962. Infestation patterns of Douglas-fir beetle in standi and windthrown trees in southern Idaho. J. Econ. Entomol. 55:486-491.

Describes characteristic infestation zones in standing and windthrown trees as a aid to efficient population sampling.

73. FURNISS, MALCOLM M. 1962. Effectiveness of DDT for preventing infestation of green logs by the Douglas-fir beetle. USDA For. Serv., Intermt. For. and Range Exp. Stn. Res. Note 96, 10 p.

Numbers of egg galleries and progeny resulting in green logs were reduced signif cantly by application of a 2% DDT emulsion spray before beetles attacked. Discusses methods to evaluate effectiveness of the spray.

74. FURNISS, MALCOLM M. 1964. A method to determine progressive mortality during seasonal development of Douglas-fir beetle brood. J. Econ. Entomol. 57:178-180

Use of a bark punch and the replacement of samples after counting permitted samp ling of the same trees at four different times, which reduced between-tree variations Mortality was high and variable early in the life of the brood. Relatively small changes occurred over winter. Makes comparisons between north and south sides of stems and between two generations.

75. FURNISS, MALCOLM M. 1965. Susceptibility of fire-injured Douglas-fir to bark beetle attack in southern Idaho. J. For. 63:8-11.

Fire injury made trees susceptible to a high incidence of beetle attack; attacks increased with tree size and severity of injury, up to but not including the death of the trees. However, attack density, rate of brood establishment (success of attack), and length of infested stem were abnormally low, due possibly to abundance of injured trees and low beetle populations.

76. FURNISS, MALCOLM M. 1965. An instance of delayed emergence of the Douglas-fir beetle and its effect on an infestation in southern Utah. J. Econ. Entomol. 58:440-442.

Documents the abrupt termination of a long-term infestation when the brood remained in infested trees for two winters. The proportions of brood stages entering fall became progressively more immature over a 4-year period before the decline, apparently because of cool weather.

77. FURNISS, MALCOLM M. 1967. Nematode parasites of the Douglas-fir beetle in Idaho and Utah. J. Econ. Entomol. 60:1323-1326.

Ectoparasites of the beetle included *Mikoletzkya* sp. (mostly), *Ektaphelencus obtusus* Massey, and *Aphelenchoides* sp. Endoparasites were: *Contortylenchus reversus* (Thorne) Rühm, *Parasitaphelenchus* sp. (both in the body cavity), and *Parasitorhabditis obtusa* (Fuchs) Dougherty (in the midgut). Parasitism rates varied little by sex of beetle; greater differences occurred between (a) localities, (b) standing and felled trees, and (c) beetles of different maturity.

78. FURNISS, MALCOLM M. 1968. Notes on the biology and effectiveness of *Karpinskiella paratomicobia* parasitizing adults of *Dendroctonus pseudotsugae*. Ann. Entomol. Soc. Am. 61:1384-1389.

Records the first known insect parasite of any adult *Dendroctonus* species. *K. paratomicobia* was found only in Utah and Arizona. Parasitized beetles laid fewer eggs and constructed shorter galleries. The parasite may lessen competition among beetle brood and increase their survival.

*79. FURNISS, MALCOLM M. 1972. Bark beetle attractants and repellants. West. For. and Conserv. Assoc., West. For. Pest Comm. Proc., p. 44-48.

Examples are given of problems involved with development of Douglas-fir beetle pheromone attractants. Frontalin strongly attracts the predacious clerid *Thanasimus undatulus* which may be destroyed in disproportionate numbers if destructive traps are used. Also, Douglas-fir beetles that aggregate to the odor of frontalin "spill over" into the surrounding stand; and beetles differ in response depending on their physiological state, making it possible that unresponsive beetles may be selected by prolonged use of pheromones. Nonetheless, attractant pheromones are useful tools for studying susceptibility of Douglas-fir in relation to root rot and in studying systematics of *T. undatulus*.

*80. FURNISS, M. M. 1976. Controlled breeding, comparative anatomy and bionomics of *Dendroctonus simplex* LeConte and *Dendroctonus pseudotsugae* Hopkins. (Coleoptera: Scolytidae). *In* Barr, W. F. (ed.), Univ. Idaho Dep. Entomol. Anniv. Publ., p. 109-120.

Intraspecific pairings were more productive in their own hosts. *D. simplex* died in Douglas-fir without tunneling or reproducing. Forty percent of female *simplex* x mal *pseudotsugae* pairs produced progeny in larch; reciprocal pairings failed. About one-third of interspecific hybrids produced $F_2$ adults. Biological and anatomical comparisons are presented including the stridulating file, seminal rod, and antennae.

*81. FURNISS, MALCOLM M., BRUCE H. BAKER, and BRUCE B. HOSTETLER. 1976. Aggregation of spruce beetles (Coleoptera) to seudenol and repression of attraction by methylcyclohexenone in Alaska. Can. Entomol. 108:1297-1302.

Four Douglas-fir beetle pheromones were tested against spruce beetle. Seudenol was 3.5 times more attractive than was frontalin. MCH was more repressive of attraction than was *trans*-verbenol, and when MCH was present with logs infested with 20 female spruce beetles or seudenol and α-pinene, the number of attracted spruce beetles was reduced 87% and 99%, respectively.

*82. FURNISS, M. M., G. E. DATERMAN, L. N. KLINE, M. D. McGREGOR, G. C. TROSTLE, L. F PETTINGER, and J. A. RUDINSKY. 1974. Effectiveness of the Douglas-fir beetle antiaggregative pheromone methylcyclohexenone at three concentrations and spacings around felled host trees. Can. Entomol. 106:381-392.

In green felled trees, Douglas-fir beetle attacks and progeny were reduced 96% an 91%, respectively, by eluting neat MCH at ca. 0.6-1.3 g/acre/day from 1/2-dram vials a 10-ft spacing. Lower and higher concentrations were not significantly better than con trols but brood in trees treated with high concentration of MCH were less mature. Densities of immature stages of nine other taxa of insects, either entomophagous or commensal, were determined.

*83. FURNISS, MALCOLM M., and ROBERT L. FURNISS. 1972. Scolytids (Coleoptera) on snowfields above timberline in Oregon and Washington. Can. Entomol. 104:1471-1478.

Douglas-fir beetles were found in small numbers (1 to 7) on snowfields above timberline on Middle Sister Mountain, Mt. Hood, Mt. Adams, and Mt. Rainier in the Cascade Range.

84. FURNISS, M. M., L. N. KLINE, R. F. SCHMITZ, and J. A. RUDINSKY. 1972. Tests of three pheromones to induce or disrupt aggregation of Douglas-fir beetles in live trees. Ann. Entomol. Soc. Am. 65:1227-1232.

Trees baited with frontalin were attacked, but mostly unsuccessfully, and few beetles were trapped. 3-methyl-2-cyclohexen-1-one disrupted attraction and may be useful for preventing attack. The role of *trans*-verbenol was not clear.

85. FURNISS, M. M., and P. W. ORR. 1970. Douglas-fir beetle. USDA For. Serv., For. Pest Leafl. 5 (Rev.), 4 p.

Summarizes the beetle's geographic range, hosts, damage caused, infestation symp-toms, description of stages, and seasonal history and control.

86. FURNISS, M. M., and R. F. SCHMITZ. 1971. Comparative attraction of Douglas-fir beetles to frontalin and tree volatiles. USDA For. Serv. Res. Pap. INT-96, 16 p.

Among 30 treatments, log sections infested with 50 virgin females were most attra tive, followed by frontalin with resin and frontalin with α-pinene. More males than females responded. Data on 26 other insects, including a new species of *Hylurgops*, a included.

*87. FURNISS, M. M., J. W. YOUNG, M. D. McGREGOR, R. L. LIVINGSTON, and D. R. HAMEL. 1977. Effectiveness of controlled-release formulations of MCH for preventing Douglas-fir beetle (Coleoptera:Scolytidae) infestation in felled trees. Can. Entomol. 109:1063-1069.

Controlled-release formulations consisting of 2% MCH in inert granules were applied around green, felled trees in spring prior to beetle attack. Two formulations equaled the liquid standard treatment in reducing densities of beetle attacks and brood. They were a wax coated molecular sieve and dimer acid polyamide beads. Abundance of immature entomophagous insects was proportional to density of host beetle attacks; the latter were negatively correlated with abundance of *Pseudohylesinus nebulosus* (Lec.).

88. FURNISS, R. L. 1936. Bark beetles active following Tillamook fire. Timberman 37(3):21-22.

Although not normally destructive in coastal stands, Douglas-fir beetles bred in fire-injured trees after which they killed trees adjacent to the burn area.

89. FURNISS, R. L. 1941. Fire and insects in the Douglas-fir region. USDA For. Serv., Fire Control Notes 5:211-213.

During the year after the Tillamook burn, Douglas-fir beetles bred in fire injured trees. In the second and third years, they killed 200 million bd. ft. of green timber.

*90. FURNISS, ROBERT L., and V. M. CAROLIN. 1978. Western forest insects, p. 357-359. USDA For. Serv. Misc. Publ. 1339, 654 p.

Good summary of the beetle's range, hosts, habits, features, seasonal history, ecological relationships, and preventive control.

91. GIBSON, ARCHIE L. 1957. Tests of bark-penetrating insecticides to control the Douglas-fir beetle. J. Econ. Entomol. 50:266-268.

Orthodichlorobenzene, trichlorobenzene, and dichloroethyl ether in oil and ethylene dibromide in oil or emulsified in water killed broods in logs and trees. Wet bark lowered the kill. Use of emulsion spray would reduce transportation costs.

92. HAGEN, K. S., and L. E. CALTAGIRONE. 1968. A new nearctic species of *Karpinskiella*. Pan-Pac. Entomol. 44:241-248.

Describes *K. paratomicobia*, the only known insect parasite of any adult *Dendroctonus* species (*D. pseudotsugae* Hopk.).

93. HAGENSTEIN, W. D., and R. L. FURNISS. 1956. Cooperation speeds salvage of windthrown and beetle-killed timber in Oregon and Washington. Soc. Am. For. Proc., 1955:167-168.

Wind and beetles killed 15 billion bd. ft. of Douglas-fir timber during 1951-1954. The Northwest Forest Pest Action Committee organized a cooperative detection survey which provided information to assist salvage operations. Two and one-half billion bd. ft. were salvaged by December 1954, and operations were continuing.

*94. HAMEL, D. R., R. D. OAKES, M. D. McGREGOR, and R. C. LOOD. 1975. Evaluation of Douglas-fir beetle infestations, North Fork Clearwater River drainage, Idaho--1974. USDA For. Serv., North. Reg., Insect and Dis. Rep. 75-11, 8 p.

Characteristics of a declining outbreak are described. Average size of loss groups was 0.65 acre containing 17 attacked trees, of which 65% were killed. Dead trees were larger than trees that survived attack. Gallery density was less and brood/parent ratio was greater and brood were more mature than during the preceding 3 years. In order of abundance, entomophagous insects were *Coeloides brunneri*>*Medetera* spp.>Cleridae.

*95. HANOVER, JAMES W. 1975. Physiology of tree resistance to insects. Annu. Rev. Entomol. 20:75-95.

Examples of resistance to Douglas-fir beetle include trees of high oleoresin exudation pressure or high β-pinene content; and live western larch (which are virtually immune to successful attack) as opposed to felled larch which beetles readily infest successfully.

96. HANOVER, J. W., and M. M. FURNISS. 1966. Monoterpene concentration in Douglas-fir in relation to attack by the Douglas-fir beetle. *In* Second Genet. Workshop, Soc. Am. For., and 7th Lake States For. Tree Improv. Conf. Joint Proc., p. 23-28. Oct. 21-23, 1965. USDA For. Serv. Res. Pap. NC-6.

Reports the identity and relative concentration of six monoterpenes of inland Douglas-fir. The influences of season, tree characteristics, viscosity, and locality on monoterpenes were investigated. Concentration of myrcene and an unknown monoterpene differed between unattacked trees and trees that resisted attack.

97. HARWOOD, W. G., and J. A. RUDINSKY. 1966. The flight and olfactory behavior of checkered beetles (Coleoptera: Cleridae) predatory on the Douglas-fir beetle. Oreg. State Univ., Agric. Exp. Stn. Tech. Bull. 95, 36 p.

Describes the environmental conditions that accompany flight of *Enoclerus sphegeus*, *E. lecontei*, and *Thanasimus undatulus*. Response of these predators to vapors of oleoresins and monoterpenes is reported and discussed.

*98. HEDDEN, R. L., and R. I. GARA. 1976. Spatial attack pattern of a western Washington Douglas-fir beetle population. For. Sci. 22:100-102.

Distance between beetle attacks was measured in mid-June on 0.372 $m^2$ samples at four locations on the upper side of the trunk of 15 felled trees (26.7 cm d.b.h., 50 yr old). Of 60 sample locations, 33 were infested. Attacks averaged 18.9/$m^2$ (SD 13.3), 26 cm apart, 13.4 cm between "nearest neighbor" and were regularly spaced (not randomly or clumped), as determined by analyses of departure from normal and index of dispersion. Probable cause of regular spacing was "interactions between female beetles" and not solely the available attack sites (crevices) or sonic interaction among females or short range repellent pheromones.

99. HEIKKENEN, HERMAN J., and BJORN F. HRUTFIORD. 1965. *Dendroctonus pseudotsugae*: A hypothesis regarding its primary attractant. Science 150:1457-1459.

The hypothesis states that beetles are attracted to host trees by α-pinene but repelled by β-pinene. Proportion of monoterpenes is suggested as a mechanism involved with beetle susceptibility.

100. HOPKINS, A. D. 1921. Contributions toward a monograph of the scolytid beetles. I. The genus *Dendroctonus*. 1909. II. Preliminary classification of the superfamily Scolytoidea. 1915. USDA, Bur. Entomol. Tech. Ser. 17, Part I, p. 1-164; Part II, p. 165-247.

Contains description of adult, pupa, larva, galleries, distribution, and hosts. Though often overlooked, this is the original reference to secondary sex characters on the penultimate tergite (p. 36-37) and elytral declivity (p. 121).

101. HOPPING, GEORGE R. 1932. Control of Douglas-fir bark beetles. Timberman 33(7): 61.

Contains recommendations to reduce amount of timber lost to bark beetles in logging operations.

102. HOPPING, GEORGE R. 1942. Apparent negative geotropism in the Douglas fir bark beetle. Can. Entomol. 74:205.

Adult Douglas-fir beetles showed negative geotropism (i.e., tunneled upward) in felled trees on 15° or steeper slopes.

103. HOPPING, GEORGE R. 1947. Notes on the seasonal development of *Medetera aldrichii* Wheeler (Diptera: Dolichopidae) as a predator of the Douglas-fir bark-beetle *Dendroctonus pseudotsugae* Hopkins. Can. Entomol. 79:150-153.

Describes the life cycle and effectiveness of *Medetera aldrichii* as a predator of *Dendroctonus pseudotsugae*.

*104. HUGHES, P. R. 1973. *Dendroctonus*: production of pheromones and related compounds in response to host monoterpenes. Z. Angew. Entomol. 73:294-312.

Retention time of chromatographic peaks indicated presence of ipsdienol in *D. pseudotsugae* males that were exposed to myrcene. After mating, two female specific compounds (including seudenol) decreased.

*105. IBARAKI, A., and T. S. SAHOTA. 1976. Effect of insect growth regulators on the survival of Douglas-fir beetle progeny. Can. For. Serv., Bimon. Res. Notes 32(1):3,5.

Of 10 insect growth regulators (IGR) screened, only ZR-515 reduced hatching and larval development when applied topically up to 100 mg/parent beetle. When ER-515 was applied at 50 mg/beetle to the abdominal venter or to phloem as 0.2% water emulsion, gallery length and egg production were unaffected but phloem treatment reduced percentage hatch and survival of larvae. Therefore, IGR is not transmitted to the egg and larval stages by adults.

106. JANTZ, ORLO K., and RICHARD L. JOHNSEY. 1964. Determination of sex of the Douglas-fir beetle *Dendroctonus pseudotsugae* Hopkins (Coleoptera: Scolytidae). Can. Entomol. 96:1327-1329.

Character of the elytral declivity proved to be the most satisfactory, rapid, and accurate method for sexing live Douglas-fir beetles.

107. JANTZ, O. K., and J. A. RUDINSKY. 1965. Laboratory and field methods for assaying olfactory responses of the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins. Can. Entomol. 97:935-941.

The attraction produced by female beetles inserted into logs of several tree species was compared with a laboratory walkway and in the field. Frass extracts of all tree species arrested beetles in walkway tests but to varying degree. Western larch was the only host attacked outside the perimeter of attraction of infested Douglas-fir logs. Brood was established, in reduced numbers, within the perimeter of attraction in ponderosa pine, western hemlock, and western white pine, which are normally nonhosts. Grand fir logs were not attacked.

108. JANTZ, O. K., and J. A. RUDINSKY. 1966. Studies of the olfactory behavior of the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins. Oreg. State Univ., Agric. Exp. Stn. Tech. Bull. 94, 38 p.

Logs containing virgin females were more attractive than tree volatiles, uninfeste logs, or logs containing reemerged females. Of the host volatiles tested, 2-1/2% resin α-pinene, and limonene attracted the most beetles. Attraction suddenly decreased immed ately after mating. Presents histological study of the gut and seasonal and diurnal flight.

109. JOHNSEY, R. L., W. P. NAGEL, and J. A. RUDINSKY. 1965. The Diptera *Medetera aldrichii* Wheeler (Dolichopodidae) and *Lonchaea furnissi* McAlpine (Lonchaeidae) associated with the Douglas-fir beetle in western Oregon and Washington. Can. Entomol. 97:521-527.

Immature Douglas-fir beetles were preyed upon but the teneral adults were rarely attacked by third-instar larvae of *Medetera aldrichii*. Third-instar larvae of *Lonchaea furnissi* did not attack the beetles in any stage during laboratory studies. Emergence patterns from infested Douglas-fir and effects of temperature and light on emergence and flight are discussed.

110. JOHNSON, NORMAN E. 1960. Douglas-fir beetle: A problem analysis. Weyerhaeuser Co., For. Res. Note 29, 19 p. + appendix.

Reviews and references, by subject, the literature prior to 1960 and proposes a research program.

111. JOHNSON, NORMAN E. 1960. Reduction of risk of losses by the Douglas-fir beetle and ambrosia beetles: An interim guide. Weyerhaeuser Co., For. Res. Note 34, 8 p.

Recommends removal of windthrow, particularly that in shade, to prevent populatio buildup. Safest felling season to avoid Douglas-fir beetle is late summer; that to avoid ambrosia beetles is spring.

112. JOHNSON, NORMAN E. 1962. Rearing of Douglas-fir beetle broods in waxed slabs. Ann. Entomol. Soc. Am. 55:659-663.

Survival of beetle broods in waxed slabs was dependent on the degree of wax covering and width of the slab.

113. JOHNSON, NORMAN E. 1963. Factors influencing the "second-attack" of the Douglas-fir beetle--Progress 1960-1962. Weyerhaeuser Co., For. Res. Note 53, 14 p.

In laboratory experiments, moisture content of the sapwood was the determining factor for when beetles leave the first gallery and start constructing another. Field tests showed that second attacks did not peak, but were more or less continuous throug out the summer.

114. JOHNSON, NORMAN E. 1963. Effects of different drying rates and two insecticide on beetle attacks in felled Douglas-fir and western hemlock. Weyerhaeuser Co., For. Res. Note 58, 16 p.

Douglas-fir beetles attacked limbed, limbed and bucked, and unlimbed Douglas-fir (but not hemlock) equally. Brood survival was lowest in unlimbed trees that dried mo rapidly. BHC and endosulfan insecticide treatments significantly reduced or eliminate Douglas-fir beetle attacks on test bole sections.

115. JOHNSON, NORMAN E. 1967. The influence of temperature and moisture on the ove wintering mortality of the Douglas-fir beetle, *Dendroctonus pseudotsugae*, in Western Washington (Coleoptera: Scolytidae). Ann. Entomol. Soc. Am. 60:199-20

In field and laboratory studies, "hardened-off" adults survived cold, wet conditions better than callow adults, pupae, or larvae.

116. JOHNSON, NORMAN E., and P. G. BELLUSCHI. 1969. Host-finding behavior of the Douglas-fir beetle. J. For. 67:290-295.

A case history is drawn from observation of an infestation following the Columbus Day storm of 1962. Beetles attacked injured trees (felled, broken off, or leaning over) and then spilled over into live surrounding trees. Gives suggestions to alleviate damage.

117. JOHNSON, NORMAN E., and MALCOLM M. FURNISS. 1967. Controlled breeding of the Douglas-fir beetle, *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae), from Idaho and coastal Washington. Ann. Entomol. Soc. Am. 60:31-33.

Crossmatings of beetles from Idaho and Washington produced fertile offspring, but in fewer numbers than did matings of beetles from a single locality.

118. JOHNSON, NORMAN E., and H. DAVID MOLATORE. 1961. X-ray detection of Douglas-fir beetles reared in slabs. Can. Entomol. 93:928-931.

Brood development in waxed slabs was traced reliably using X-ray detection in all stages except immature larvae.

119. JOHNSON, NORMAN E., P. W. ORR, and K. H. WRIGHT. 1959. Beetle hazard in windthrown Douglas-fir. Weyerhaeuser Timber Co., For. Res. Note 20, 3 p.

Shaded windthrow had more Douglas-fir beetle attacks and a higher percentage of brood survival than did exposed windthrow.

120. JOHNSON, NORMAN E., and LEON F. PETTINGER. 1961. Douglas-fir beetle attacks in living trees as influenced by the presence of fresh windthrow. Weyerhaeuser Co., For. Res. Note 37, 8 p.

All standing trees within 3 ft of newly-downed trees were attacked in a 100-yr-old stand; attacks decreased as the distance from downed trees increased. Beetles were induced to attack other standing trees that had 1-ft sections of uninfested, newly-cut Douglas-fir next to them.

121. JOHNSON, NORMAN E., and LEON F. PETTINGER. 1961. Overwintering mortality of Douglas-fir beetles in infested logs, exposed bark and forest litter in western Washington. Weyerhaeuser Co., For. Res. Note 42, 11 p.

Approximately one-half of adult beetles survived over winter in loose bark and forest litter. Larval survival was similar. Eighty-four percent of the beetles survived in undisturbed bark of windthrown trees.

122. JOHNSON, NORMAN E., K. H. WRIGHT, and P. W. ORR. 1961. Attack and brood survival by the Douglas-fir beetle in four types of windthrown trees in western Washington. Weyerhaeuser Co., For. Res. Note 40, 13 p.

Attacks and brood survival were highest in shaded windthrown trees.

123. KEEN, F. P. 1952. Insect enemies of western forests. USDA, Div. For. Insect Invest., Bur. Entomol. and Plant Quar., Misc. Publ. 273:155-158.

Briefly discusses Douglas-fir beetle damage, biology, and control. [Supplanted by Furniss and Carolin, 1978].

124. KHAN, M. A. 1957. *Sphaerularia bombi* Duf. (Nematoda: Allantonematidae) infesting bumblebees and *Sphaerularia hastata* sp. nov. infesting bark beetles in Canada. Can. J. Zool. 35:519-523.

*Sphaerularia hastata* infests adult Douglas-fir beetles in British Columbia.

125. KHAN, M. A. 1957. *Sphaerularia ungulacauda* sp. nov. (Nematoda: Allantonematidae) from the Douglas-fir beetle *Dendroctonus pseudotsugae* Hopk., with key to *Sphaerularia* species (Emended). Can. J. Zool. 35:635-639.

Describes *Sphaerularia ungulacauda* from adult Douglas-fir beetles in British Columbia.

126. KHAN, M. A. 1960. Descriptions of two nematodes, *Ektaphelenchus macrostylus* n.sp., and *Laimaphelenchus ulmi* n.sp., with a key to species of *Laimaphelenchus*. Can. J. Zool. 38:91-97.

Female *Ektaphelenchus marcostylus* were taken from Douglas-fir beetles; males were found in the bark of Douglas-fir.

127. KHAN, M. A. 1960. *Stictylus hastatus* (Khan 1957) n. comb., and *Stictylus ungulacaudus* (Khan 1957) n. comb. (Nematoda: Neotylenchidae). Can. J. Zool. 38:225-226.

Transfers these two nematode parasites of the Douglas-fir beetle from the genus *Sphaerularia* Dufour to the genus *Stictylus* Thorne.

128. KIMMEY, J. W., and R. L. FURNISS. 1943. Deterioration of fire-killed Douglas-fir U.S. Dep. Agric. Tech. Bull. 851, 61 p.

Douglas-fir beetles are among the first insects to attack Douglas-fir killed by a fire, usually during the following spring. The beetle is important because it introduce fungi, including blue-stain, which speeds deterioration of the sapwood. Deterioration rate is discussed by causes, tree characteristics, and environmental factors.

129. KINGHORN, J. M. 1953. Chemical control of bark beetles. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 9(4):4.

Douglas-fir beetle was completely controlled by spraying infested logs with 0.8 lb ethylene dibromide/gal in a 20% oil emulsion.

130. KINGHORN, J. M. 1955. Chemical control of mountain pine beetle and Douglas-fir beetle. J. Econ. Entomol. 48:501-504.

Two systemic insecticides (Systox and schradan) and four bark sprays (ethylene dibromide, heptachlor, aldrin, and lindane) were applied to trees and logs. Ethylene dibromide was most effective.

131. KINGHORN, J. M. 1957. An induced differential bark beetle attack. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 13(2):3-4.

Short sections cut from felled trees and then aged were not attacked by Douglas-fi beetles but longer stem pieces left in the woods were readily infested. Inverse result occurred with the striped ambrosia beetles.

132. KINGHORN, J. M., and W. WEBB. 1950. Chemical control of ambrosia beetles. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 6(6):3-4.

Benzene hexachloride in oil or as an emulsion spray significantly reduced Douglas-fir beetle attacks on test logs.

133. KINZER, G. W., A. F. FENTIMAN, JR., R. L. FOLTZ, and J. A. RUDINSKY. 1971. Bark beetle attractants: 3-methyl-2-cyclohexen-1-one isolated from *Dendroctonus pseudotsugae*. J. Econ. Entomol. 64:970-971.

3-methyl-2-cyclohexen-1-one was extracted and identified from hindguts of female Douglas-fir beetles. Greater numbers of walking male beetles were arrested by the compound in mixture with frontalin than by either frontalin or the compound alone. Frontalin was identified from female hindguts, and three other biologically active compounds also were isolated.

134. KLINE, L. N., and J. A. RUDINSKY. 1964. Predators and parasites of the Douglas-fir beetle: Description and identification of the immature states. Oreg. State Univ., Agric. Exp. Stn. Tech. Bull. 79, 52 p.

Describes eggs, larval instars, and pupae of principal predators and parasites. Discusses rearing procedures and measurement and drawing methods.

135. KNOPF, J. A. E., and G. B. PITMAN. 1972. Aggregation pheromone for manipulation of the Douglas-fir beetle. J. Econ. Entomol. 65:723-726.

Douglure (a mixture of frontalin, α-pinene, and camphene) in polyethylene containers was applied to 157 live Douglas-fir trees. By June 25, all treated trees, but only 8% of the control trees, were attacked. Attack density was $12+/\text{ft}^2$. Within 33 ft of baited trees, 58% of the Douglas-fir were attacked, as compared to 4% surrounding control trees. Beetles attacked proportionately more of the large trees surrounding the treated trees. The average infested height of treated trees was 36% shorter than that of control trees.

*136. LANIER, GERALD N., and WENDELL E. BURKHOLDER. 1974. Pheromones in speciation of Coleoptera. *In* Birch, M. C. (ed.), Pheromones, p. 161-189. North Holland Publishing Co., Amsterdam, 495 p.

Examples include references to Douglas-fir beetle cross attraction with spruce beetle and southern pine beetle and role of pheromones (and hosts) in reproductive isolation.

137. LeJEUNE, R. R., L. H. McMULLEN, and M. D. ATKINS. 1961. The influence of logging on Douglas-fir beetle populations. For. Chron. 37:308-314.

Beetle outbreaks can be prevented by measures designed to minimize presence of breeding material; logging of overmature stands; and cutting in a manner designed to trap and remove beetles.

*138. LIBBEY, L. M., M. E. MORGAN, T. B. PUTNAM, and J. A. RUDINSKY. 1976. Isomer of antiaggregative pheromone identified from male Douglas-fir beetle: 3-methylcyclohex-3-en-1-one. J. Insect Physiol. 22:871-873.

3,3-MCH, a polar isomer of 3,2-MCH [referred to as MCH in earlier literature], was identified from male-released volatiles. Originally designated peak "A" (Rudinsky and others 1973), 3,3-MCH was released by males in greater quantity than either of two other pheromones: 3,2-MCH or frontalin. It was absent in unfed females.

139. LINDQUIST, EVERT E. 1969. Mites and the regulation of bark beetle populations. Second Int. Congr. Acarol. Proc., 1967:389-399.

Indicates that the egg predator, *Seius safroi* Ewing [see Bedard 1937] is currently *Lasioseius safroi* (Ewing) (= *dendroctoni* Chant). Other predacious or parasitic species associated with the Douglas-fir beetle are *Digamasellus* sp., *Proctolaelaps hystricoides* Lind. & Hunter, and *P. subcorticalis* Lind.

140. LINDQUIST, EVERT E. 1971. New species of Ascidae (Acarine: Mesotigmata) associated with forest insect pests. Can. Entomol. 103:919-942.

Douglas-fir beetle is mentioned as one host for *Proctolaelaps subcorticalis* Lind. in British Columbia.

*141. LOOK, MELVIN. 1976. Determining release rates of 3-methyl-2-cyclohexen-1-one antiaggregation pheromone of *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae). Chem. Ecol. 2:481-486.

MCH eluted from 5 g samples of controlled release formulations was trapped for 1 to 2 h on Porapak-QS, then analyzed by HPLC. Results were as accurate as determinations using tritium-labeled MCH and were obtained more quickly and accurately than with gas chromatography for samples with low release rate. Additional advantages to HPLC were: (1) larger samples could be injected and (2) solvent peaks did not mask the MCH peak.

142. LU, K. E., DONALD G. ALLEN, and WALTER B. BOLLEN. 1957. Association of yeasts with the Douglas-fir beetle. For. Sci. 3:336-343.

Cultured yeasts from beetles were identified as *Saccharomyces pastoria*, *Candida parapsilosis*, *C. mycoderma*, and *Hensenula capsulata*. When presented to live beetles, odors of the four yeasts combined and of *S. pastoria* alone evoked positive response; beetles rejected *C. parapsilosis* and *C. mycoderma* (each alone) in favor of the control arm of the olfactometer.

143. LYON, R. L. 1958. A useful secondary sex character in *Dendroctonus* bark beetles. Can. Entomol. 90:582-584.

The sex of *Dendroctonus* beetles can be readily and accurately determined by the shape of the seventh abdominal tergite.

144. LYON, ROBERT L. 1965. Structure and toxicity of insecticide deposits for control of bark beetles. USDA For. Serv. Tech. Bull. 1343, 59 p.

Reviews results of spray tests conducted on bark beetles including the Douglas-fir beetle.

145. McALPINE, J. F. 1964. Descriptions of new Lonchaeidae (Diptera). II. Can. Entomol. 96:701-757.

Describes *Lonchaea furnissi*, which is associated with Douglas-fir beetle egg galleries; it occurs in Idaho, Oregon, Washington, and British Columbia.

146. McCOWAN, V. F., and JULIUS A. RUDINSKY. 1958. Biological studies on the Douglas-fir bark beetle, Millicoma Forest, Coos Bay, Oregon. Weyerhaeuser Timber Co., For. Res. Note 14 (Rev.), 21 p.

Contains important information on seasonal history, sampling, distribution of brood and attacks in standing trees and in windthrow trees, natural enemies, amount of mortality by stem position and time, relation of growth to susceptibility, and associated insects and fungi.

147. McGHEHEY, J. H., and W. P. NAGEL. 1966. A technique for rearing larvae of *Medetera aldrichii* (Diptera: Dolichopodidae). Ann. Entomol. Soc. Am. 59:290-292.

A study of four media to develop a suitable technique for rearing the larval stages of *Medetera aldrichii* on its host *Dendroctonus pseudotsugae*. Douglas-fir phloem mixture was the only successful medium.

*148. McGREGOR, M. D., W. E. BOUSFIELD, and DEWEY ALMAS. 1972. Evaluation of the Douglas-fir beetle infestation in the North Fork Clearwater River drainage, Idaho--1972. USDA For. Serv., North. Reg., Insect and Dis. Rep. I-72-10, 9 p.

During 1970-1972, Douglas-fir beetles killed 17.6% (109 million bd. ft.) of the merchantable Douglas-fir volume. Mortality was estimated by use of 161, 1:8000 scale photo plots and 24, 100-acre ground plots. Film used in 1972 was true color Kodak SO-397.

*149. McGREGOR, M. D., M. M. FURNISS, W. E. BOUSFIELD, D. P. ALMAS, PAUL J. GRAVELLE, and R. D. OAKES. 1975. Evaluation of the Douglas-fir beetle infestation, North Fork Clearwater River drainage, northern Idaho, 1970-1973. USDA For. Serv., North Reg., For. Insect and Dis. Rep. 74-7, 17 p.

An outbreak that began in 1969 killed 114.6 million bd. ft. of Douglas-fir during 1971-1973. Mortality was measured on 1:8000 scale aerial photographs and 100-ac plots. Compared by year are infested trees and stands; populations of Douglas-fir beetle; and entomophagous insects. Number of infested trees per group declined from 158 to 22. Proportion of unsuccessfully attacked trees varied from 31% to 59%. Brood/parent ratios declined from 1.0 to 0.82. Entomophagous insects in order of abundance were *Coeloides brunneri*>*Medetera* spp.>Cleridae and *Temnochila chlorodia*.

*150. McLEAN, J. A., and J. H. BORDEN. 1977. Attack by *Gnathotrichus sulcatus* (Coleoptera: Scolytidae) on stumps and felled trees baited with sulcatol and ethanol. Can. Entomol. 109:675-686.

Douglas-fir beetles infested only Douglas-fir stumps and logs; not western hemlock, and were not responsive to treatments involving sulcatol or ethanol. Attacks increased through May, peaked June 21, then continued at low levels through August. Attacks averaged 19/m$^2$ and were confined to logs >14 cm diameter.

151. McMULLEN, L. H. 1956. A note on the mortality of the Douglas-fir beetle in the interior of British Columbia during the winter of 1955-56. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 12(6):3-4.

Callow adult mortality of nearly 75 percent seemed to be caused by sudden severe cold weather in early November.

152. McMULLEN, L. H. 1970. Extended life cycle of Douglas-fir beetle in interior British Columbia. Can. Dep. Fish. and For., For. Serv., Bimon. Prog. Rep. 26(5):46.

A report of two instances in which brood remained in trees for 2 years.

*153. McMULLEN, L. H. 1977. Douglas-fir beetle in British Columbia. Can. For. Serv. Pest Leafl. 14, 6 p.

Briefly describes life stages, life history, and damage. Recommends preventive and remedial measures such as sanitation, salvage, use of trap trees, and destruction of brood.

154. McMULLEN, L. H., and M. D. ATKINS. 1959. A portable tent-cage for entomological field studies. Entomol. Soc. B.C. Proc. 56(4):67-68.

Describes a tent-cage of nylon netting, 6 ft long with 4 ft wide floor and sides, used to study Douglas-fir beetles in logs under field conditions.

155. McMULLEN, L. H., and M. D. ATKINS. 1959. Life-history and habits of *Scolytus tsugae* (Swaine) (Coleoptera: Scolytidae) in the interior of British Columbia. Can. Entomol. 91:416-426.

*S. tsugae* infested Douglas-fir stems mainly 2.5 to 7 inches diameter at a density of 20 attacks/ft$^2$. Flight and attacks occurred between May 22 and July 30, peaking between June 17 and July 16. The female constructs its egg gallery longitudinally, scoring the sapwood resulting in whitish boring dust, whereas that of *Pseudohylesinus nebulosus* is reddish. Galleries have a turning niche at their middle, average 2.01 inch long and 1.65 mm wide compared to 1.21 mm for *Scolytus unispinosus*. The life cycle is 1 year; larvae overwinter mainly in the terminal fourth instar. In a cage containing green pieces of 10 species of trees, *Pinus monticola* was infested most densely.

156. McMULLEN, L. H., and M. D. ATKINS. 1961. Intraspecific competition as a factor in the natural control of the Douglas-fir beetle. For. Sci. 7:197-203.

As crowding increased, parents abandoned their egg galleries more rapidly; egg galleries were shorter, contained fewer eggs, and mortality of larvae and pupae was higher. Maximum absolute production of adult brood occurred at attack densities of [illegible]/ft$^2$. Relative increase in progeny per parent was inversely proportional to attack density; it declined to 1:1 at 13 to 17 attacks/ft$^2$.

157. McMULLEN, L. H., and M. D. ATKINS. 1962. On the flight and host selection of the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopk. (Coleoptera: Scolytidae). Can. Entomol. 94:1309-1325.

Beetles flew in spring when temperatures reached 65° to 70°F for a few days. Newly-felled trees were more attractive than trees felled 15 days or more. At high temperature, attacks were heavier on the underside. Initial attack by females created a strong attraction, which increased with number of females present. Presence of males in galleries reduced attractiveness.

158. McMULLEN, L. H., and J. WALTERS. 1956. Transplanting larvae of *Dendroctonus pseudotsugae* Hopk. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 12(3):3-4.

Larvae were transplanted from brood logs to holes made in uninfested logs. Survival was [illegible] to 40 percent and 50 to 100 percent in punched and chiseled holes, respectively.

159. MASSEY, CALVIN L. 1966. The genus *Mikoletzkya* (Nematoda) in the United States. Helminthol. Soc. Wash. Proc. 33:13-19.

Contains description of *Mikoletzkya diluta* associated with the Douglas-fir beetle.

160. MASSEY, CALVIN L. 1967. Nematodes associated with tree-infesting insects: Paurondontidae new family and Misticiinae new subfamily with a description of one new genus and four new species. Can. J. Zool. 45:779-786.

[illegible] *mustus* was recovered from Douglas-fir beetle galleries in New Mexico.

161. MASSEY, CALVIN L. 1969. New species of tylenchs associated with bark beetles in New Mexico and Colorado. Helminthol. Soc. Wash. Proc. 36:43-52.

Describes the nematode *Neoditylenchus puniwopus* in association with Douglas-fir beetles from New Mexico.

*162. MASSEY, CALVIN L. 1974. Biology and taxonomy of nematode parasites and associates of bark beetles in the United States. USDA For. Serv. Agric. Handb. 446, 233 p.

Fourteen species of ecto- and endoparasitic nematodes are listed from *D. pseudotsugae* including a new species, *Parasitaphelencus beccus* from Moscow Mountain, Idaho.

163. MATHERS, W. G. 1951. Douglas-fir beetle [in British Columbia]. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 7(3):3.

In a 250-year-old stand, susceptibility was correlated with slow growth and injury (including windthrow) but not dominance or size.

164. MICHAEL, R. R., and J. A. RUDINSKY. 1972. Sound production in Scolytidae: specificity in male *Dendroctonus* beetles. J. Insect Physiol. 18:2189-2201.

The male stridulatory apparatus (pars stridens on the left elytron and plectrum on the seventh abdominal tergite) was measured and described from scanning electron micrographs. Sound properties of "chirps" were analyzed for number, rate, and duration of tooth strikes. Chirps were evoked using either the natural female attractant (frass) or four synthetic components. Compared to the mountain pine beetle, the sounds made by the Douglas-fir beetle were species specific.

*165. MITCHELL, RUSSEL G., and CHARLES SARTWELL. 1974. Insects and other arthropods. *In* Environmental effects of forest residues management in the Pacific Northwest, p. R-1 - R-22. USDA For. Serv. Gen. Tech. Rep. PNW-24.

Felled trees and logging residue are important because they influence beetle host selection, size of beetle population, and thereby, mortality of standing trees.

*166. NIJHOLT, W. W., and T. S. SAHOTA. 1974. Changes in triglyceride fatty acids during brood production of Douglas-fir beetles (Coleoptera: Scolytidae). Can. Entomol. 106:927-932.

Beetles and eggs were analyzed for total lipid and triglyceride (fatty acid) content 0 to 21 days after infestation of logs. Triglycerides formed 97% of total lipids in the eggs. After 4 days, total lipids and triglycerides increased in adults of both sexes. Oleic acid was predominant among six fatty acids identified. Palmitic acid increased with time, whereas palmitoleic acid decreased. Percentages of oleic acid and linoleic acid varied reciprocally by sex over time. Physiological bases and implications of these findings are discussed.

167. PITMAN, G. B. 1973. Further observations on Douglure in a *Dendroctonus pseudotsugae* management system. Environ. Entomol. 2:109-112.

Douglure applied to trees singly and in groups resulted in attacks on 67.1 percent and 68.5 percent, respectively, of the trees within 1 chain distance. Height of attacks was less in baited trees than in surrounding attacked trees. Sticky boards, containing Douglure, entrapped only 8.6 Douglas-fir beetles/$ft^2$. One *Thanasimus undatulus* as caught per bark beetle.

*168. PITMAN, G. B., R. L. HEDDEN, and R. I. GARA. 1974. Synergistic effects of ethyl alcohol on the aggregation of *Dendroctonus pseudotsugae* (Col., Scolytidae) in response to pheromones. Z. Angew. Entomol. 78:203-208.

Addition of seudenol to Douglure (4:1:1 mix of frontalin, α-pinene, and camphene) significantly increased its attractiveness. Further increase in attractiveness occurred with addition of ethyl alcohol which seemed capable of replacing synergistic terpenes in the attractant mix. Sex ratio of responding beetles varied considerably among tests but generally favored males.

169. PITMAN, G. B., and J. P. VITÉ. 1970. Field response of *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae) to synthetic frontalin. Ann. Entomol. Soc. Am. 63: 661-664.

Among 7 treatments, frontalin plus camphene attracted the most beetles (4♂:1♀) and large numbers of the clerid *Thanasimus undatulus* Say. Frontalin induced attack when applied to live trees. Frontalin appeared in female hindguts within 24 h after feeding and disappeared by 48 h.

*170. PITMAN, G. B., and J. P. VITÉ. 1974. Biosynthesis of methylcyclohexenone by male Douglas-fir beetle. Environ. Entomol. 3:886-887.

MCH was produced by unmated male beetles in greater amount than by unmated females that were fed or not fed. Feeding stimulated females to produce seudenol and *trans*-verbenol.

171. RENWICK, J. A. A., and J. P. VITÉ. 1968. Isolation of the population aggregating pheromone of the southern pine beetle. Contrib. Boyce Thompson Inst. 24(4): 65-68.

Gas chromatography showed that female Douglas-fir beetles have a compound in common with the female southern pine beetle and male western pine beetle. In field tests, crushed, emerged female Douglas-fir beetles attracted southern pine beetles.

172. RICHERSON, J. V., and J. H. BORDEN. 1971. Sound and vibration are not obligatory host finding stimuli for the bark beetle parasite, *Coeloides brunneri* (Hymenoptera: Braconidae). Entomophaga 16:95-99.

*Coeloides brunneri* discerned different stages of host in Douglas-fir beetle-infested logs and oviposited through bark only onto older larvae. The parasite was also able to locate and oviposit on larvae that had been freeze-killed.

173. RICHERSON, J. V., and J. H. BORDEN. 1972. Host finding behavior of *Coeloides brunneri* (Hymenoptera: Braconidae). Can. Entomol. 104:1235-1250.

Describes four distinct phases of host finding: random search; nonrandom search; ovipositional; and nonsearch (resting and cleaning). Amputation showed that the antennae are the principal host-finding receptor organs. Sounds, magnetism, and odor were not involved in host finding.

174. RICHERSON, J. V., and J. H. BORDEN. 1972. Host finding by heat perception in *Coeloides brunneri* (Hymenoptera: Braconidae). Can. Entomol. 104:1877-1881.

*Coeloides brunneri* females were shown to oviposit at warmer locations on bark. These "hotspots" were associated with subcortical Douglas-fir beetle larvae. When a heated wire was inserted in bark, oviposition behavior was induced. The evidence supports the argument that *C. brunneri* locates its host through perception of infrared radiation.

175. RICHERSON, J. V., J. H. BORDEN, and J. HOLLINGDALE. 1972. Morphology of a unique sensillum placodeum on the antennae of *Coeloides brunneri* (Hymenoptera: Braconidae). Can. J. Zool. 50:909-914.

Describes a unique antennal placoid sensillum; its anatomy suggests that it directs infrared radiation during location of host larvae such as the Douglas-fir beetle.

*176. RINGOLD, G. B., P. J. GRAVELLE, D. MILLER, M. M. FURNISS, and M. D. McGREGOR. 1975. Charactersitics of Douglas-fir beetle infestation in northern Idaho resulting from treatment with Douglure. USDA For. Serv. Res. Note INT-189, 10 p.

An average of nine trees was attacked within 2 chains of those treated with Douglure. Beetles were unsuccessful (no larval mines were present) in 56% of the attacked trees. Successfully attacked trees were larger, and attacks in them were of greater density and extended to greater height. Baited trees were more susceptible to attack than were spillover trees.

177. ROSS, D. A. 1967. Wood and bark-feeding Coleoptera of felled western larch in British Columbia. J. Entomol. Soc. B.C. 64:23-24.

Includes Douglas-fir beetle in a list of Coleoptera reared from western larch.

178. RUDINSKY, J. A. 1961. Factors affecting the population density of bark beetles. Thirteenth Congr. Int. Union For. Res. Organ., Vienna, Proc. I: Sec. 24-11, 13 p.

Biotic factors affecting Douglas-fir beetle abundance include intraspecific competition and entomophages. Moisture affects resin pressure that is $<1\text{-}1/2$ atm. in susceptible trees. Susceptible trees also are invaded more rapidly by blue stain fungi and have low pH.

179. RUDINSKY, J. A. 1962. Ecology of Scolytidae. Annu. Rev. Entomol. 7:327-348.

The Douglas-fir beetle is referred to somewhat incidentally and for illustrative purposes in this broad review of scolytid ecology.

180. RUDINSKY, J. A. 1963. Response of *Dendroctonus pseudotsugae* Hopkins to volatile attractants. Contrib. Boyce Thompson Inst. 22:23-38.

Attraction of flying beetles resulted only from virgin female beetles feeding in phloem. The attractive substance was present in frass and excrement and was soluble in petroleum ether. Response of beetles to field olfactometers baited with logs infested with females exhibited a distinct diurnal and seasonal pattern influenced by environmental factors, mainly temperature.

181. RUDINSKY, J. A. 1966. Host selection and invasion by the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins, in coastal Douglas-fir forests. Can. Entomol. 98:98-111.

More females than males respond to odors of volatile terpenes in resin, which provide primary (host) attraction to flying beetles. Trees of insufficient oleoresin exudation pressure (OEP) are invaded successfully by females, which creates a secondary attraction and results in mass concentration (favoring males) of additional beetles. However, trees having high OEP resist attacking beetles either by repelling them with concentrated vapors or by suffocating them.

182. RUDINSKY, J. A. 1966. Observations on olfactory behavior of scolytid beetles (Coleoptera: Scolytidae) associated with Douglas-fir forests. Z. Angew. Entomol. 58(4):356-361.

In the field, Douglas-fir beetles were attracted to logs containing females, in a ratio of 3 males to 1 female. Ethanol extract from female frass was more attractive than uninfested logs. Attractive host volatiles were camphene, resin, α-pinene, and limonene.

183. RUDINSKY, JULIUS A. 1966. Scolytid beetles associated with Douglas-fir: response to terpenes. Science 152:218-219.

Response of Douglas-fir beetle (and other scolytids) to host volatiles was studied. Most attractive in the following order were camphene, resin, α-pinene, limonene, and logs. Responding females outnumbered males 2:1.

184. RUDINSKY, J. A. 1968. Pheromone-mask by the female *Dendroctonus pseudotsugae* Hopk., an attraction regulator (Coleoptera: Scolytidae). Pan-Pac. Entomol. 44:248-250.

Male stridulation or mating resulted in cessation of attraction created by females in bark. Attraction was reestablished within 10 min by removal of stridulating males from close proximity to unmated females. The mask was restricted to the area near the female entry hole; thus it permitted colonization of uninfested parts of the host tree.

185. RUDINSKY, J. A. 1969. Masking of the aggregation pheromone in *Dendroctonus pseudotsugae* Hopk. Science 166:884-885.

Attraction created by virgin females feeding in phloem was masked suddenly by male stridulation. Attack density is thereby regulated without disrupting the mating of the arrested male.

186. RUDINSKY, J. A. 1969. Studies on timber beetles. *In* Insect-plant interactions, p. 64-65. Natl. Acad. Sci., Washington, D.C.

Mentions chemical studies underway on the pheromone of *Dendroctonus pseudotsugae*.

187. RUDINSKY, J. A. 1970. Sequence of Douglas-fir beetle attraction and its ecological significance. Contrib. Boyce Thompson Inst. 24:311-314.

Flying female beetles were attracted weakly to host tree volatiles in a ratio favoring females. As the females bored into the bark, they produced pheromones that created a strong secondary attraction favoring males. Male stridulation at a gallery entry stimulated the female to release a short-range masking substance that abruptly terminated the attractiveness to other males. However, this mask did not deter the stridulating male nor terminate primary attraction.

*188. RUDINSKY, J. A. 1973. Multiple functions of the Douglas-fir beetle pheromone, 3-methyl-2-cyclohexen-1-one. Environ. Entomol. 2:579-585.

Addition of MCH diluted in alcohol at 0.01% and 0.001%, increased the attractiveness of frontalin and host terpenes, and attracted a high proportion of males. Higher concentrations of MCH (0.5% to 2%) repressed attraction. MCH was recovered from feces of fed virgin females in lesser amount than frontalin.

*189. RUDINSKY, JULIUS A. 1974. Method for the control of the Douglas-fir beetle. U.S. Patent Office, Patent No. 3,830,935.

Consists of two claims: (1) a method of protecting trees from attack by use of MCH and (2) delivery method (glass vials inside perforated cans) [methodology is that of Rudinsky and others, 1972 (Can. Entomol.)].

*190. RUDINSKY, J. A. 1976. Various host-insect interrelations in host-finding and colonization behavior of bark beetles on coniferous trees. Symposia Biologica Hungarica, Tihany, Hungaria, June 11-14, 1974, 16:229-235.

Host tree terpenes aid *Dendroctonus* spp. in host recognition; and enhancement and biosynthesis of aggregating pheromones. Terpinolene is probably a precursor of the antiaggregative pheromone MCH, which in turn could be reduced to the aggregating pheromone seudenol by female Douglas-fir beetles. Because many bark beetle species share the same host attractants and pheromones, acoustic signals have evolved in concert with pheromone communication. The gallery-establishing sex has "quiet" sonic signals suited to transmission in a dense medium (bark); the other sex often begins stridulating outside the gallery and has louder stridulation more capable of airborne transmission.

191. RUDINSKY, J. A., and G. E. DATERMAN. 1964. Field studies on flight patterns and olfactory responses of ambrosia beetles in Douglas-fir forests of western Oregon. Can. Entomol. 96:1339-1352.

*Gnathotrichus sulcatus* Lec. and *G. retusus* Lec. were strongly attracted to logs infested with female Douglas-fir beetles; *Trypodendron lineatum* (Oliv.) was not attracted.

192. RUDINSKY, J. A., M. M. FURNISS, L. N. KLINE, and R. F. SCHMITZ. 1972. Attraction and repression of *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae) by three synthetic pheromones in sticky traps in Oregon and Idaho. Can. Entomol. 104:815-822.

The attractiveness of frontalin and host volatiles was confirmed, but addition of 3-methyl-2-cyclohexen-1-one disrupted attraction and reduced by up to 96 percent the number of beetles caught. Males were repressed more than females. The role of *trans*-verbenol was not clear.

193. RUDINSKY, J. A., G. W. KINZER, A. F. FENTIMAN, JR., and R. L. FOLTZ. 1972. *Trans*-verbenol isolated from Douglas-fir beetle: laboratory and field bioassays in Oregon. Environ. Entomol. 1:485-488.

*Trans*-verbenol decreased to nil after 48 h in female beetles from Idaho, but still was detectable after 72 h in Oregon beetles. In the laboratory, arrestment of walking beetles increased with lower concentration of *trans*-verbenol. In the field, flying beetles were arrested only if frontalin also was present.

*194. RUDINSKY, J. A., L. N. KLINE, and J. D. DIEKMAN. 1975. Response-inhibition by four analogues of MCH, an antiaggregative pheromone of the Douglas-fir beetle. J. Econ. Entomol. 68:527-528.

Four analogues of MCH: pipertone, pulegone, methone, and 3-methylcyclohexenone significantly decreased attraction of Douglas-fir beetles to natural (female infested logs) and synthetic attractants (frontalin + camphene). Response of the clerid, *Thanasimus undatulus* Say and sex ratios of *D. pseudotsugae* were not strongly affected by the analogues.

195. RUDINSKY, J. A., and R. R. MICHAEL. 1972. Sound production in Scolytidae: Chemostimulus of sonic signal by the Douglas-fir beetle. Science 175:1386-1390.

Almost all males stridulated in response to female-produced frass but up to 88% also responded to combinations of synthetic pheromones and host tree volatiles. Female attraction ceased abruptly when subjected to the sound of a live stridulating beetle or to a recording of the sound.

196. RUDINSKY, J. A., and R. R. MICHAEL. 1973. Sound production in Scolytidae: stridulation by female *Dendroctonus* beetles. J. Insect Physiol. 19:689-705.

Female beetles possess stridulatory apparatus on the last sternite and inside the top of the left elytron (similar to males). Solitary females emit an infrequent click whereas rapid clicks or multiple chirps are evoked by close proximity of other females of the same species. These sounds may regulate attack spacing.

*197. RUDINSKY, J. A., M. MORGAN, L. M. LIBBEY, and R. R. MICHAEL. 1973. Sound production in Scolytidae: 3-methyl-2-cyclohexen-1-one released by female Douglas-fir beetle in response to male sonic signal. Environ. Entomol. 2: 505-509.

Male stridulation, either from live beetles or recorded and played back, stimulate unfed females to release MCH and an unidentified compound. [The pheromones were collected from live, newly emerged, unfed beetles--an important advance in identification technology.] MCH could be biosynthesized by beetles from terpinolene, a constituent of Douglas-fir oleoresin.

*198. RUDINSKY, J. A., M. E. MORGAN, L. M. LIBBEY, and T. B. PUTNAM. 1974. Additiona components of the Douglas-fir beetle (Col., Scolytidae) aggregative pheromone and their possible utility in pest control. Z. Angew. Entomol. 76:65-77.

MCH-ol [= seudenol = peak "3", Rudinsky 1973] and verbenone were released when males were near unmated, fed females, bringing the total of known female produced pheromones to five. Other unidentified compounds were released. Evaporation rates are given for the five pheromones under field conditions, frontalin being most volatile. α-pinene or dilutions of MCH and *trans*-verbenol synergized seudenol; responding beetles were mainly males. Undiluted verbenone repressed response; diluted verbenone enhanced response.

*199. RUDINSKY, J. A., M. E. MORGAN, L. M. LIBBEY, and T. B. PUTNAM. 1976. Release of frontalin by male Douglas-fir beetle. Z. Angew. Entomol. 81:267-269.

Unfed live males confined together 24 h released frontalin and two other pheromones, 3,2-MCH and 3,3-MCH.

*200. RUDINSKY, J. A., M. E. MORGAN, L. M. LIBBEY, and T. B. PUTNAM. 1976. Limonene released by the scolytid beetle *Dendroctonus pseudotsugae* . Z. Angew. Entomol 82:376-380.

Stimulated by playback of recorded stridulation sounds of the opposite sex, both female and male *D. pseudotsugae* released limonene in amounts greater than control beetles without stridulation sound. Limonene was absent in dead males; females had a trace amount. Limonene composes up to 8% of oleoresin of inland Douglas-fir but sourc of limonene released by beetles is not known although test beetles had not been expose to a fresh resinous atmosphere. Limonene could benefit attacking beetles by synergizi aggregative pheromones.

*201. RUDINSKY, J. A., and L. C. RYKER. 1976. Olfactory and auditory signals mediat behavioral patterns of bark beetles. Coll. Int. CNRS No. 265 - Comportment de Insects et Milieu Trophique (Tours, France), Sept. 13-17, 1976, p. 195-209.

Excellent summary of long term studies of chemical and sonic signals in relation to (mainly) Douglas-fir beetle behavior. Included are effects of host volatiles, aggregative, and antiaggregative pheromones. Host oleoresin volatiles, especially α-pinene, camphene, and limonene attract pioneer female beetles and also serve as precursors and synergists of attractant pheromones. During colonization of trees, female stridulation regulates attack spacing. Female frass contains attractant consisting of five known components, some being multi-functional at extremes of concentration. The male reacts to female attractant by stridulating in a manner that causes the female to release 3,2-MCH which in turn evokes in the male a change in chirp and release of 3,2-MCH, 3,3-MCH, and frontalin which together mask attraction. This behavioral chain has been documented naturally and induced experimentally by synthetic female and male chirps.

*202. RUDINSKY, J. A., and L. C. RYKER. 1976. Sound production in Scolytidae: rivalry and premating stridulation of male Douglas-fir beetle. J. Insect Physiol. 22:997-1003.

Male attractant chirps (short, continuous) changed to rivalry chirps (long, interrupted) in presence of other males or during a premating period while in the female gallery. 3,2-MCH and frontalin, released by both sexes, evoked the male interrupted chirp. Varying concentrations of MCH reversed its arrestment effect on walking males. Rivalry behavior of male-female pairs diminished with time after females fed and mating was preceded by a switch by males to a courtship chirp (simple uninterrupted) and cooperative behavior. Mating and stridulation in plexiglass chambers are described.

*203. RUDINSKY, J. A., L. C. RYKER, R. R. MICHAEL, L. M. LIBBEY, and M. E. MORGAN. 1976. Sound production in Scolytidae: female sonic stimulus of male pheromone release in two *Dendroctonus* beetles. J. Insect Physiol. 22:1675-1681.

Four pheromones, released during actual and synthesized stridulation sounds of males and females, were measured. Male pheromones were released in greater quantity in presence of female stridulation than without sonic stimulus or with recorded male stridulation. The order of amount released was: 3,3-MCH>3,2-MCH>frontalin; MCH-ol (seudenol) was absent. Females released 3,2-MCH but mainly seudenol and frontalin in response to male stridulation. Thus, each sex released its pheromones at the sonic signal of the other, and masking of attraction appears to result from combined release of pheromones by both sexes.

*204. RUDINSKY, J. A., C. SARTWELL, JR., T. M. GRAVES, and M. E. MORGAN. 1974. Granular formulation of methylcyclohexenone: an antiaggregative pheromone of the Douglas-fir and spruce bark beetles. Z. Angew. Entomol. 75:254-263.

MCH was demonstrated for the first time to be produced by spruce beetles in placing unmated pairs together in glass tubes. Although not as effective as liquid MCH diffused from glass vials, a 3.6% MCH corn cob formulation significantly reduced spruce beetle attacks in windthrown Sitka spruce but not Douglas-fir beetle attacks in windthrown Douglas-fir. Attacks increased somewhat 30 days after treatment. Predacious insect density was unaffected by treatment. *Ips* spp. were concentrated in the upper trunk; *Hylurgops rugipennis* was most abundant on the shaded side.

205. RUDINSKY, J. A., and PAVEL SVIHRA. 1971. The patterns of water ascent in conifers. Acta Inst. For., Zvolen, Czech. II:369-383.

[Deals mainly with five patterns of ascent found in conifers.] Water ascends in Douglas-fir in a sectorial, winding manner. This pattern allows a large lateral portion of a growth ring to be supplied from each and enables the tree to restore water balance quickly during rainy weather. Restoration of water balance results in resinosis, which repels beetles and prevents spread of blue stain fungi.

206. RUDINSKY, J. A., and L. C. TERRIERE. 1959. Laboratory studies on the relative contact and residual toxicity of ten test insecticides to *Dendroctonus pseudotsugae* Hopk. J. Econ. Entomol. 52:485-488.

Lindane at LD 50 and Thiodan at LD 90 were most toxic but DDT lasted longest of all insecticides that were applied to a wood fiber surface.

207. RUDINSKY, J. A., L. C. TERRIERE, and D. G. ALLEN. 1960. Effectiveness of various formulations of five insecticides on insects infesting Douglas-fir logs. J. Econ. Entomol. 53:949-953.

Emulsions and solutions of endrin, lindane, Thiodan, Sevin, and heptachlor protected logs from Douglas-fir beetle attack. In the laboratory, suspensions were less effective on logs but had higher residual toxicity on wood fiber surfaces.

208. RUDINSKY, J. A., and J. P. VITÉ. 1956. Effects of temperature upon the activity and the behavior of the Douglas-fir beetle. For. Sci. 2:258-267.

Reports on a study of relationships of temperature to limits of beetle activity, boring rate, flight (duration, velocity), and running; and reactions to light.

209. RUDINSKY, J. A., and O. ZETHNER-MØLLER. 1967. Olfactory responses of *Hylastes nigrinus* (Coleoptera: Scolytidae) to various host materials. Can. Entomol. 99:911-916.

Flying *H. nigrinus* were strongly attracted to stumps of trees killed by the Douglas-fir beetle.

210. RUMBOLD, CAROLINE T. 1936. Three blue-staining fungi, including two new species, associated with bark beetles. J. Agric. Res. 52:419-437.

Describes *Ceratostomella pseudotsugae*, a blue-stain fungus associated with Douglas-fir beetle.

211. RUST, H. J. 1933. Many bark beetles destroyed by predacious mite. J. Econ. Entomol. 26:733-734.

Refers to an instance in which 62.5% of Douglas-fir beetle eggs died, presumably caused mainly by mites.

212. RYAN, ROGER B. 1959. Termination of diapause in the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins (Coleoptera: Scolytidae), as an aid to continuous laboratory rearing. Can. Entomol. 91:520-525.

New adult beetles undergo an obligatory diapause, during which they are incapable of either flight or reproduction. This condition is reflected by undeveloped main fligh muscles and gonads. Diapause was broken [as indicated by emergence] most effectively by 90 days' exposure to 39° to 49°F, followed by rearing at 75°F. A generation was completed in a minimum of 146 days.

213. RYAN, R. B. 1962. Durations of the immature stadia of *Coeloides brunneri* (Hymenoptera: Braconidae) at various constant temperatures, with descriptions of the five larval instars. Ann. Entomol. Soc. Am. 55:403-409.

Reports on the duration of immature stadia at various temperatures and describes the five larval instars.

214. RYAN, ROGER B. 1962. A device for measuring the oviposition potential of a bark beetle parasite. Can. Entomol. 94:137-138.

Describes construction and use of a device to determine the percentage of log circumference where bark thickness is less than the mean ovipositor length of *Coeloides brunneri* Vier.

215. RYAN, ROGER B. 1965. Maternal influence on diapause in a parasitic insect, *Coeloides brunneri* Vier. (Hymenoptera: Braconidae). J. Insect Physiol. 11: 1331-1336.

Diapause of progeny was determined by the photoperiod and temperature to which parent females were exposed.

216. RYAN, ROGER B., and JULIUS A. RUDINSKY. 1962. Biology and habits of the Douglas-fir beetle parasite, *Coeloides brunneri* Viereck (Hymenoptera: Braconidae), in western Oregon. Can. Entomol. 94:748-763.

Comprehensively describes seasonal history; behavior during mating; searching and oviposition; host size and its influence on sex of progeny; longevity; oöcyte maturation and fecundity; and relationship between parasitism and bark thickness. A plan is proposed for manipulating the parasite to control the beetle.

217. SAHOTA, T. S. 1970. Haemolymph and ovarial proteins in the bark beetle, *Dendroctonus pseudotsugae* in relation to ovarian development. Can. J. Zool. 48:1307-1312.

Two female-specific blood proteins increased to a maximum 48 h after infestation of logs. Their incorporation into ovaries lagged by about 24 h; possibly, this is controlled by concentration of juvenile hormone.

218. SAHOTA, T. S. 1971. Failure of ovarian development in the Douglas-fir bark beetle, *Dendroctonus pseudotsugae*; an analysis of gut proteases and female-specific proteins. Can. J. Zool. 49:1021-1024.

Although provided suitable diet, female beetles that are outside their normal gallery environment fail to reproduce. Study indicates that proteolytic enzymes in guts of females are adequate and that lack of juvenile hormone may be responsible for absence of ovarian development.

*219. SAHOTA, T. S. 1973. Yolk deposition in Douglas-fir beetle oöcytes: possible role of RNA synthesis in the follicular epithelium. J. Insect Physiol. 19:1087-1095.

Juvenile hormone appears to affect deposition of yolk protein by controlling RNA synthesis in follicle cells. Injection of the antibiotic actinomycin D inhibited synthesis of DNA-dependent RNA in follicular epithelium and blocked yolk deposition in oöcytes and prevented oviposition for 72 to 96 h, past the normal onset.

*220. SAHOTA, T. S. 1975. Effect of juvenile hormone on acid phosphatases in the degenerating flight muscles of the Douglas-fir beetle, *Dendroctonus pseudotsugae*. J. Insect Physiol. 21:471-478.

Acid phosphatase positive sites in flight muscles increased within 24 h after beetles fed on phloem indicating that muscle degeneration had begun. Phosphatase activity increased with topical application of juvenile hormone (JH). Injection of the nerve stimulant, eserine, did not prevent JH from causing muscle degeneration, but, because only certain muscles degenerate, the nervous system, not a circulating hormone, must be involved in this specificity.

221. SAHOTA, T. S., J. A. CHAPMAN, and W. W. NIJHOLT. 1970. Ovary development in a scolytid beetle *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae): effect of farnesyl methyl ether. Can. Entomol. 102:1424-1428.

Ovarian development was stimulated naturally by introduction of females to logs, o unnaturally stimulated by treatment with the gonadotrophic hormone, = farnesyl methyl ether.

*222. SAHOTA, T. S., and A. IBARAKI. 1973. Yolk deposition in the Douglas-fir bark beetle, *Dendroctonus pseudotsugae* (Hopk.): the significance of physiological state of oocytes. Can. J. Zool. 51:659-661.

Presence of radioactive proteins in ovaries was determined for beetles that burrowed in bark for 24 to 96 h. Yolk proteins were present in ultimate (most mature) oöcytes beginning at 48 h; and in penultimate and even younger oöcytes thereafter. Presence of juvenile hormone in the incubation medium did not affect these results; physiological state of oöcytes did.

223. SCHMIDT, FRED H. 1966. Two artificial (oligidic) media for the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopk. (Coleoptera: Scolytidae). Can. Entomol. 98:1050-1055.

Under xenic conditions, both media shortened the rate of brood development compare to previous published data. Adults appeared to be normal; females laid viable eggs.

224. SCHMITZ, RICHARD F., and JULIUS A. RUDINSKY. 1968. Effect of competition on survival in western Oregon of the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins (Coleoptera: Scolytidae). Oreg. State Univ. For. Res. Lab., Res. Pap. 8, 42 p.

In controlled laboratory and field tests, intraspecific competition decreased survival when densities exceeded 2 attacks, 50-100 larval mines, or 19 inches of egg gallery per ft$^2$. Interspecific competition was not a factor in natural control.

225. SCHOFER, G. A., and G. N. LANIER. 1970. A sexual character in pupae of *Dendroctonus* (Coleoptera: Scolytidae). Can. Entomol. 102:1487-1488.

Though Douglas-fir beetle pupae were not examined, a lobe between the 8th sternit and 9th tergite is present in females but absent in males of several *Dendroctonus* species; this is suggested as a possible generic character.

226. SMITH, H. W., and M. M. FURNISS. 1966. An automatically recording insect fligh mill. Can. Entomol. 98:249-252.

Describes specifications and instructions for an automatically recording insect flight mill. Revolutions of individual flight mills are recorded, by photocells, on electric counters.

227. SMYTH, ARTHUR V. 1959. The Douglas-fir bark beetle epidemic on the Millicoma Forest: methods used for control and salvage. J. For. 57:278-280.

Because of deterioration, timber must be salvaged within 10 years after being killed by beetles. Systematic survey and maintenance of access roads are necessary if prompt sanitation cutting and salvage are to be effective.

*228. ST. CLAIR, A., R. L. GOULDING, and J. A. RUDINSKY. 1977. Controlled release dispensing system for 3,2-MCH, antiaggregative pheromone of the Douglas-fir beetle (Col. Scolyt.). Z. Angew. Entomol. 83:297-300.

Attraction created by logs containing 10 female Douglas-fir beetles was inhibited during a 3-day test by 3,2-MCH diffused at 0.12 to 0.48 mg/h from 6 mil polyethylene envelopes.

229. STOSZEK, K. J., and J. A. RUDINSKY. 1967. Injury of Douglas-fir trees by maturation feeding of the Douglas-fir Hylesinus, *Pseudohylesinus nebulosus* (Coleoptera: Scolytidae). Can. Entomol. 99:310-311.

*Pseudohylesinus nebulosus* feeding may be a contributing factor to Douglas-fir beetle attacks on healthy trees.

230. THOMAS, J. B. 1965. The immature stages of Scolytidae: The genus *Dendroctonus* Erichson. Can. Entomol. 97:374-400.

Provides keys and illustrations for separating larvae and pupae of *Dendroctonus* species. *D. pseudotsugae* larvae differ from *D. simplex* in size, roughness of frons, and basal part of the mandibles. Pupae display differences in the setae on the body and head.

231. THOMAS, J. B. 1967. A comparative study of gastric caeca in adult and larval stages of bark beetles (Coleoptera: Scolytidae). Entomol. Soc. Ont. Proc. 97(1966):71-90.

Describes and compares caeca on the midgut of Douglas-fir beetle larvae and adults to other *Dendroctonus*.

232. THOMPSON, S. N., and R. B. BENNETT. 1971. Oxidation of fat during flight of male Douglas-fir beetles, *Dendroctonus pseudotsugae*. J. Insect Physiol. 17: 1555-1563.

Flying male beetles utilized predominantly fatty acids, particularly monosaturates followed by saturates.

*233. TRAPPE, JAMES M. 1953. Review of the Douglas-fir beetle epidemic in western Oregon and Washington and investigation of reduced tree vigor as a causal factor. Coll. For., Univ. Wash., Seattle, 24 p. (typed).

Annual radial growth was determined for 66 pairs of dominant or codominant Douglas-firs; one member of each pair was alive, the other was beetle-killed in 1951 or 1952. Growth of the dead members had declined during the 4 years preceding infestation. Cause of diminished growth was not determined.

234. VITÉ, J. P. 1968. Timber industry attacks bark beetle problem through basic research. Tex. Ind. 36(Sept.):14-16.

Large quantities of frontalin were found in female *Dendroctonus pseudotsugae*.

235. VITÉ, J. P. 1970. Erste Anwendung synthetischer Populationslockstoffe in der Borkenkäferbekämpfung. Allg. Forstz. 25:615-616.

Research at Boyce Thompson Institute has led to the discovery of frontalin as a principal population-aggregating pheromone of *Dendroctonus pseudotsugae*.

236. VITÉ, J. P. 1970. Pest management systems using synthetic pheromones. Contrib. Boyce Thompson Inst. 24:343-350.

Advocates baiting live Douglas-fir trees, within blocks of timber to be clearcut, with frontalin, α-pinene, and camphene.

237. VITÉ, J. P., G. B. PITMAN, A. F. FENTIMAN, JR., and G. W. KINZER. 1972. 3-methyl-2-cyclohexen-1-ol isolated from *Dendroctonus*. Die Naturwissenschaften 10:469-470.

The bicyclic ketal 3-methyl-2-cyclohexen-1-ol was theoretically predicted to be a possible attractant for *D. pseudotsugae*. Its natural presence in that beetle as well as *D. rufipennis* (Kirby) was confirmed by chemical analyses.

238. VITÉ, J. P., and J. A. RUDINSKY. 1957. Contribution toward a study of Douglas-fir beetle development. For. Sci. 3:156-167.

Describes characteristics, including larval head widths, of all stadia and their duration at different temperatures. The characteristics of the ovaries are shown in relation to age and reproductive history. Some males demonstrated that they were polygamous.

239. VITÉ, J. P., and J. A. RUDINSKY. 1962. Investigations on the resistance of conifers to bark beetle infestation. XI Int. Kongr. Entomol., Wien 1960. Sonderdr. Verh. II:219-225.

Oleoresin exudation pressure (o.e.p.) in Douglas-fir reaches equilibrium more slowly and is less than in ponderosa pine. Pressure is lowest during intensive growth, in trees infected by the fungus *Fomes pini* (Thore) Lloyd, and in windthrown trees.

240. WALTERS, H., and K. GRAHAM. 1952. The Douglas-fir beetle problem in the interior of British Columbia. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 8(5):3.

Twenty-three infestations (10 to 350 trees each) were examined. Beetle infestations usually were found where logging operations had produced excess slash and in overmature stands.

241. WALTERS, J. 1955. Douglas-fir beetle associated with winter injury. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 11(4):2-3.

In old-growth Douglas-fir stands, tree mortality increased rapidly after winter injury.

242. WALTERS, J. 1956. Biology and control of the Douglas-fir beetle in the interior of British Columbia. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Publ. 975, 11 p.

Describes life history and habits of the beetle; also discusses practices to prevent and control outbreaks.

243. WALTERS, J., and D. K. CAMPBELL. 1955. Mites as agents of natural control of the Douglas-fir beetle. Can. Dep. Agric., For. Biol. Div. Sci. Serv., Bimon. Prog. Rep. 11(1):3-4.

Logs were infested with 109 mite-free and 124 mite-infested beetles. Reduction of brood (presumably by mites) averaged 26 percent. Predation was considerably less on second brood of reemerged parents. Species involved were *Calvolia* sp., *Dendrolaelaps quadrisetis* (Berl.), *Lasioseius* sp., *Parasitus* sp., and *Uropoda* sp., prob. *michiganensis* Vitz.

244. WALTERS, J., and L. H. McMULLEN. 1956. Life history and habits of *Pseudohylesinus nebulosus* (Leconte) (Coleoptera: Scolytidae) in the interior of British Columbia. Can. Entomol. 88:197-202.

*P. nebulosus* is the first bark beetle to infest felled Douglas-fir trees in the pring. Attacks average $51/ft^2$ (max. 122). Infested bark may be unsuitable for attacks y the Douglas-fir beetles. An average of 18 eggs are laid per gallery (max. 43). arvae have three instars. One generation occurs per year; young adults overwinter in iches in bark.

245. WASHBURN, R. I. 1965. Douglas-fir beetle problems, Dixie National Forest [Utah]. USDA For. Serv., Intermt. Reg., Div. Timber Manage., Ogden, Utah, 15 p. + 8 figs. (typed).

Outbreaks occurred in 1907; 1933-1937; 1940-1942; and 1950-1963. During the last utbreak, beetles killed 100 million bd. ft. (57% of the standing Douglas-fir) in 11 nfested areas sampled. Twenty sample trees averaged 197 years old, 15.5 inches d.b.h., 5 ft tall, and were infested to an average height of 22 ft. [Of interest historically nd because no other damage estimate is available for southern Utah.]

46. WEAR, J. F., and J. R. DILWORTH. 1955. Color photos aid salvage of beetle-killed Douglas-fir timber as mapping technique is developed. Lumberman 82:88-89, 132-133.

Color photos greatly facilitated the location of infestations to help in planning ogging operations. Comparison of ground and photocounts showed that some intermediate rees and most suppressed trees will be missed in photocounts. Compares advantages and isadvantages of aerial color transparencies to black and white photography, including ost.

47. WEAR, J. F., and P. G. LAUTERBACH. 1956. Color photography useful in evaluating mortality of Douglas-fir. Soc. Am. For. Proc. 1955:169-171.

Aerial color photos greatly aided evaluation of mortality caused by the Douglas-ir beetle. Nearly twice as many errors occurred when interpreting panchromatic prints s compared to color. Use of color transparencies also facilitated location of ecently-killed trees.

48. WEAR, J. F., R. B. POPE, and P. G. LAUTERBACH. 1962. Estimating beetle-killed Douglas-fir by aerial photo and field plots. J. For. 62:309-315.

A large number of color photoplots combined with ground-checking a small number f field plots proved to be a reliable and economical method to estimate beetle damage.

49. WEAR, J. F., R. B. POPE, and P. W. ORR. 1966. Aerial photographic techniques for estimating damage by insects in western forests. USDA For. Serv., Pac. Northwest For. and Range Exp. Stn., 79 p.

Presents sampling methods using aerial photos to estimate (a) amount of Douglas-fir eetle damage and (b) its location for salvage. Gives recommendations for film and cale.

50. WEISER, JAROSLAV. 1970. Three new pathogens of the Douglas-fir beetle, *Dendroctonus pseudotsugae: Nosema dendroctonia* n.sp., *Ophryocystis dendroctonis* n.sp., and *Chytridiopsis typographi* n. comb. J. Invert. Pathol. 16:436-441.

The respectively named protozoan parasites generally occurred at low rates in alpighian tubules, fat bodies, some muscles, malpighian tubules; and epithelial cells f the midgut. The fungus, *Beauvaria bassiana*, infected dead adult beetles.

51. WERT, STEVEN L., and BRUCE ROETTGERING. 1968. Douglas-fir beetle survey with color photos. Photogramm. Eng. 34:1243-1248.

Large-scale (1:8000) aerial photos combined with stratified 2-stage probability sampling proved to be the best survey technique in terms of accuracy, time required, and costs to determine the extent of damage from beetles in northwestern California.

252. WILLIAMSON, RICHARD L., and FRANK E. PRICE. 1971. Initial thinning effects in 70- to 150-year-old Douglas-fir--western Oregon and Washington. USDA For. Serv. Res. Pap. PNW-117, 15 p.

Thinning reduced tree mortality caused by bark beetles.

253. WOOD, STEPHEN L. 1963. A revision of the bark beetle genus *Dendroctonus* Erichson (Coleoptera: Scolytidae). Great Basin Nat. 23(1-2):1-117.

Includes description of physical characteristics and biology of the Douglas-fir beetle.

254. WOODRING, J. P. 1966. North American Tyroglyphidae (Acari): I. New species of *Calvolia* and *Nanacarus*, with keys to the species. La. Acad. Sci. Proc. 29:76-84.

Describes *Calvolia furnissi*, a mite taken from galleries and frass of Douglas-fir beetles near Moscow, Idaho.

255. WOODRING, J. P. 1966. North American Tyroglyphidae (Acari): II. The genus *Schwiebia*, with descriptions of four new species. La. Acad. Sci. Proc. 29: 85-112.

Describes a mite, *Schwiebia pseudotsuga*, found in galleries of Douglas-fir beetles near Moscow, Idaho.

256. WOODRING, J. P., and J. C. MOSER. 1970. Six new species of anoetid mites associated with North American Scolytidae. Can. Entomol. 102:1237-1257.

*Bonomoia certa* was associated with Douglas-fir beetles from Moscow Mountain, Idaho

257. WRIGHT, ERNEST, and K. H. WRIGHT. 1954. Deterioration of beetle-killed Douglas-fir in Oregon and Washington. A study of findings to date. USDA For. Serv., Pac. Northwest For. and Range Exp. Stn. Res. Pap. 10, 12 p.

Describes study of decay rate in relation to tree age, ratio of sapwood to heartwood, wood borers, and intensity of beetle attack.

258. WRIGHT, K. H., and G. M. HARVEY. 1967. The deterioration of beetle killed Douglas-fir in western Oregon and Washington. USDA For. Serv. Res. Pap. PNW-50, 20 p.

This report relates wood deterioration rate to tree age and size, external tree characters, causal agent (fungus, insect), and felling breakage.

259. WRIGHT, K. H., and P. G. LAUTERBACH. 1958. A 10-year study of mortality in a Douglas-fir sawtimber stand in Coos and Douglas Counties, Oregon. USDA For. Serv., Pac. Northwest For. and Range Exp. Stn. Res. Pap. 27, 29 p.

Douglas-fir beetles accounted for 59 percent of tree mortality, followed by wind and disease. Mortality was greatest in codominant trees and on better sites.

260. WRIGHT, K. H., and R. R. LeJEUNE. 1967. Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopk. *In* Important forest insects and diseases of mutual concern to Canada, the United States and Mexico, p. 16-20. Can. Dep. For. & Rural Develop., 248 p.

Summarizes damage, distribution, life history, and control.

*261. YOUNG, J. W., T. M. GRAVES, R. CURTIS, and M. M. FURNISS. 1977. Controlled release formulations of insect growth regulators and pheromones--evaluation methods and field test results. *In* Scher, H. B. (ed.), Controlled release pesticides, p. 184-199. ACS Symp. Ser. 53, 205 p. Am. Chem. Soc., Washington, D.C.

Briefly describes laboratory method of determining release rate of tritium labeled MCH from many candidate controlled-release formulations. Five formulations that eluted at a rate >0.05 μg/h for 30 to 60 days were field tested. Two formulations (coated molecular sieve granules and dimer acid polyamide granules) equaled the liquid standard treatment.

262. ZETHNER-MØLLER, O., and J. A. RUDINSKY. 1967. On the biology of *Hylastes nigrinus* (Coleoptera: Scolytidae) in western Oregon. Can. Entomol. 99:897-911.

*Hylastes nigrinus* infests the roots of trees killed by Douglas-fir beetles. Competition with Douglas-fir beetle brood is slight.

263. ZETHNER-MØLLER, O., and J. A. RUDINSKY. 1967. Studies on the site of sex pheromone production in *Dendroctonus pseudotsugae* (Coleoptera: Scolytidae). Ann. Entomol. Soc. Am. 60:575-582.

Describes the digestive tract, malpighian tubes, and reproductive system of females. Arrestment tests using these organs from attractive females indicate that the hindgut and malpighian tubes are associated with pheromone production.

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1979. An annotated bibliography of the Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins). USDA For. Serv. Gen. Tech. Rep. INT-48 (Revises 8), 40 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

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*Back cover: A group of mature trees killed by Douglas-fir beetles.*

# PROCEEDINGS OF FIRE WORKING GROUP SOCIETY OF AMERICAN FORESTERS

National Convention
Albuquerque, New Mexico Oct. 4, 1977

COMPILED BY RICHARD J. BARNEY

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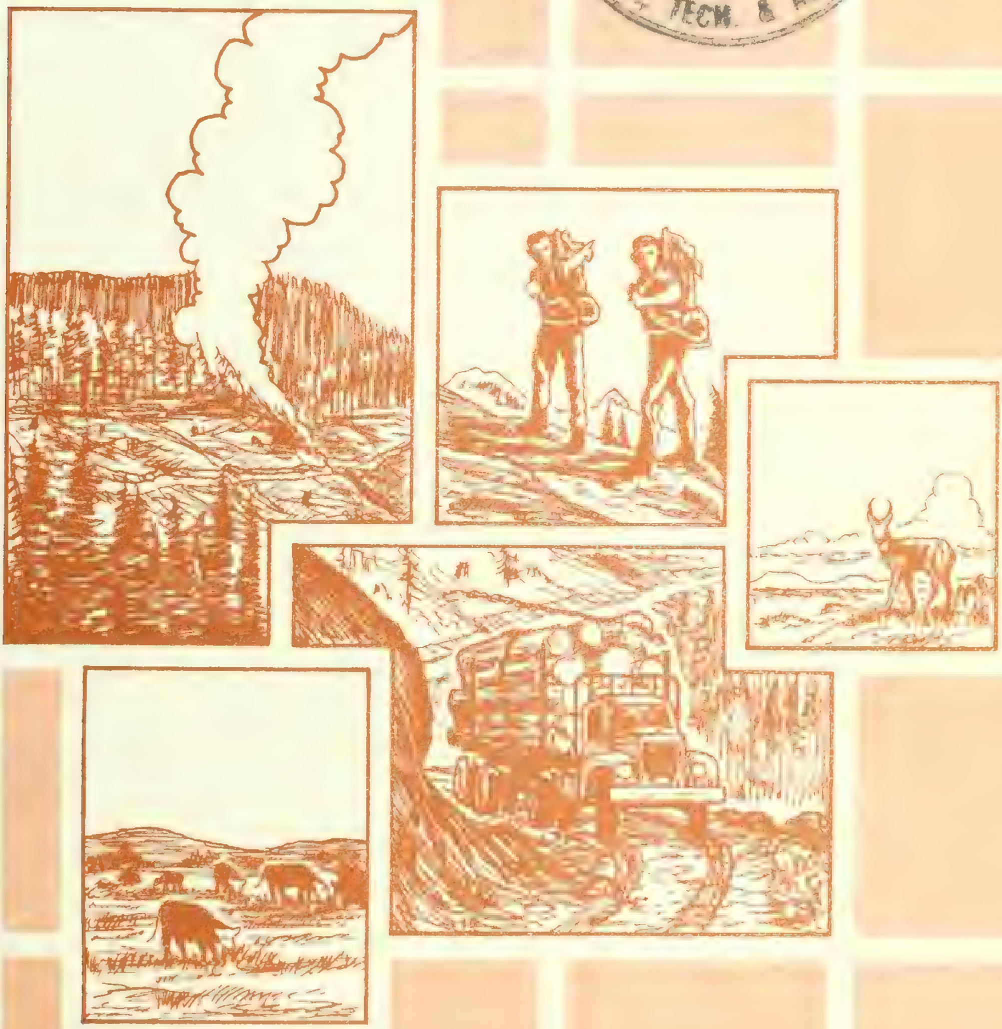

USDA Forest Service General Technical Report INT-49
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
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The Society of American Foresters, Fire Working Group, thanks the speakers for their contributions to these proceedings and all the Working Group Session participants for making it a successful session. Special thanks go to the Program Committee--David Aldrich, John Deeming, and Art Brachebusch. We also thank the Society of American Foresters for allowing us to publish these papers separately from the general meeting proceedings. Dr. James E. Lotan, Program Manager of the Fire and Multiple Use Planning Research, Development, and Application Program, is also acknowledged for his support.

We also acknowledge the Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, for publishing the meeting proceedings. It is through these kinds of cooperative efforts that professional management will be enhanced and maintained.

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April 1979

# Proceedings of Fire Working Group Society of American Foresters National Convention Albuquerque, New Mexico October 4, 1977

**Compiled by**
**Richard J. Barney**

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Ogden, Utah 84401

# PREFACE

A technical session on fire and land management planning was held by the Fire Working Group of the Society of American Foresters at the national meeting in Albuquerque, New Mexico, October 4, 1977. The purpose of this technical session was to bring together landowners, planners, and managers, as well as fire management personnel, to consider the effects of fire on the productivity of the resources we manage. It was hoped that, by such a session, individuals involved in land management planning and action could discuss a common problem heretofore not covered in such a context.

This session was a continuing attempt to maintain and develop the relevance of fire to other management activities. It was to provide the fire managers, as well as others, a current perspective and knowledge that a high quality, professional management of our natural resources could continue. This session was not all inclusive. However, by exposing the issues to a fire manager/planner/landowner audience, we hoped to clarify and provide alternatives for future communication and development.

Planning today is, perhaps, one of the most important activities of most federal land management agencies. With the changing posture of fire management, it is important that fire management be integrated into the planning process. This session was a continuing attempt to improve the fire integration process into the planning and management activities. Through such sessions and future sessions of this type, the fire working group is moving to improve and maintain the technical input and the professional competency of the products that evolve.

The papers presented in these proceedings are being published under one cover to provide improved distribution and access of information.

RICHARD J. BARNEY
Program Chairman

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# RESEARCH SUMMARY

A compilation of papers presented at the Society of American Foresters, Fire Working Group technical session held in Albuquerque, New Mexico, October 2-6, 1977. The keynote address by Dr. M. Rupert Cutler, Assistant Secretary of Agriculture established the session's perspective on Fire Management and Land Management. Subsequent papers treated information needed by the land manager: how fire-related activities could be adapted to support land management activities; using simulation as a tool; and legislation affecting forest practices involving fire.

# FIRE MANAGEMENT AND LAND MANAGEMENT

## PUTTING THEM INTO PERSPECTIVE

M. Rupert Cutler

Assistant Secretary of Agriculture for

Conservation, Research and Education

Thank you for inviting me to participate with you in this Fire Working Group Technical session. It is appropriate that the Fire Working group discuss the relationship of fire to resource management and land management planning. The topics to be discussed today are certainly timely and deserve your attention. I feel it is significant that your working group is trying to involve landowners, managers and planners.

Fire was a front page news story this summer. The severe fire situation demonstrated quite vividly the negative impact of fire. This fire season again pointed out that man is still unable to master wildfire under severe conditions. It also points out that we must consider fire in our management activities. Some of these fires were influenced by man's past and present management activities -- and many of them will drastically change man's future management actions.

## HISTORICAL PERSPECTIVE

In the late 1800's, fire control grew out of a need to protect resources from destruction. As fire control evolved, we developed some very effective fire fighting forces. Many of the time-honored principles and practices of fire control are as appropriate now as the day they were conceived. However, with changes in our information base, in sociological and political requirements, and in natural resource management objectives, it is now generally agreed that fire should be considered in its widest context.

In addition, man has been studying land use as it relates to agriculture for centuries and land use concerns have emphasized the relationship of fire to land management planning. Land use and land use planning have generated ever-increasing concern and interest since the environmental movement began in the early 60's. The National Environmental Policy Act of 1969, with its direction to Federal land agencies, added a new direction to the issue. Most recently the National Forest Management Act of 1976; the Federal Land Policy and Management Act of 1976, also know as the BLM Organic Act; as well as the Resources Planning Act of 1974; added more direction on Federal lands. In the State and private sector, there is also a growing concern and interest in land use planning.

## FIRE-RESOURCE RELATIONSHIPS

Fire by itself is neither friend nor foe. It becomes "good" or "bad," only as it relates to man's value system. If you are a wildlife manager, and fire burns an area and the result is increased sprouting of browse species important to the animals you are dealing with, then fire is "good." If, however, timber management is your goal and that area was covered by a stand of 15- to 20-year old reproduction destined for harvest in 50 to 75 years, then fire is "bad." The total benefits and damages to all resources must be considered in assessing the net effect of fire.

Fire is used to convert less desirable vegetative cover types to cover types with more desirable species composition. Fire is also used to maintain ecosystems at certain stages of succession. Many other examples can be given to show both "good" and "bad" effects of fire. Again, let me point out that fire is only "good" or "bad" when man's value system is considered.

What I am getting at is the heart of this session today: fire, both good and bad, or the lack of fire, affects the production of wildland goods and services. Fire can detract from or enhance natural resource objectives. Fire can do either or both, depending upon vegetative composition, the physiographic situation, climate, fire behavior and the desired management objectives. Therefore, fire must be considered as a resource modifier.

## FIRE MANAGEMENT AND RESOURCE MANAGEMENT

Let me discuss fire management and its role in total resource management. Fire management, is a support or service function. Dr. Richard Barney our program chairman, in an article in the Journal of Forestry, defines fire management as, ". . .the integrating of fire-related biological, ecological, physical, and technological information into land management to meet desired objectives."

Fire management is the protection from fire and the use of fire in meeting defined land management goals and objectives. Fire prevention, fire control and fire use are the basic implementing activities. All economic and ecological implications must be considered. The major justification for public or private fire management should be based on the land manager's need to reach his objectives.

Fire must also be considered in the initial stages of resource management planning, as the objectives are being established. Fire should be considered in determining whether or not the objectives is realisitic and attainable. The management objectives must also be assessed in terms of their short- and long-range effects on the fire situation within the management area. Would intensive logging creat a fuel problem? Would logging increase the probability of fire? Would the increased fuel load intensify a fire, causing effects different than those required to meet the management objectives? Fire considerations must be reviewed following implementation or simulation of the management actions initiated to meet management objectives.

Fire can exert a strong influence on management options. We must be able to predict consequences or various fire management activities. activities. This requires a knowledge of preburn conditions, the particular kinds of fire involved, and the response of the ecosystem in time. Predicting the kinds of fires that will result requires understanding the variability of fuels on the ground, the probabilities of fire weather and the probabilities of a source of ignition. This is no small task and mades the fire manager's role much more complex. He must provide special expertise in fire ecology, fire suppression, fire use, fire prevention, fuels management and economics to assist the land manager in meeting his goals and objectives.

## FIRE MANAGEMENT AND LAND MANAGEMENT PLANNING

There must be a link between land management planning and fire management planning. Land management planning is not complete without the consideration of fire. This does not mean that fire has to be a major factor in every plan, but it should be considered. On the other hand, fire could be very importa in protecting, modifying or perpetuating the ecosystem. We must also assess the potential effect of planned management actions on the future fire situation. This must all be done on an interdisciplinary basis. Without interdisciplinary consideration, we haven't done our jobs as professional managers.

From the Federal forestry side of the ledger, there are legal requirements for interdiciplinary, multifunctional planning. I believe that fire considerations are defini part of that interdiciplinary need. Regardle of whether the land is public or private, input is needed from the fire management specialist. He must assess the feasibility and the possibility of protecting a certain resource land base -- and protection is necessary both before and after a management activity. He must assess and indicate where fire can be used. He must help the other resource specialists focus on using fire to attain maximum production of a specific resource, such as timber, range or wildlife, while still protecting the environment.

Totally integrated land management plan is beginning. It is here that we can determ the kinds of activities that ought to occur a specific area. Fire planning must provide the necessary or indicated protection for th resources and must be commensurate with the values involved. Fire protection and use must support various management strategies s that the intended management goals and objectives can be reached.

## SUMMARY

My challenge to each of you, landowners managers, planners, is this -- consider fire as a resource modifier. Then, and only then will fire assure a more realistic, more defensible, and more desirable perspective i land management planning and resource management strategies. This is the role that we must play if totally integrated land management planning is to be realized.

# THE INFORMATION ABOUT FIRE NEEDED
# BY THE LAND MANAGEMENT PLANNER

William N. Lyon

State Fire Management Officer, Bureau

of Land Management, Billings, Montana

Land use planning has truly reached a high ateau in this country. Planning is firmly trenched and here to stay.

With the population increase and therefore creased resource demands, our resource procing land base is shrinking. We must strive r maximum production on the remaining land. meet this challenge, planning is essential.

## WHAT IS PLANNING?

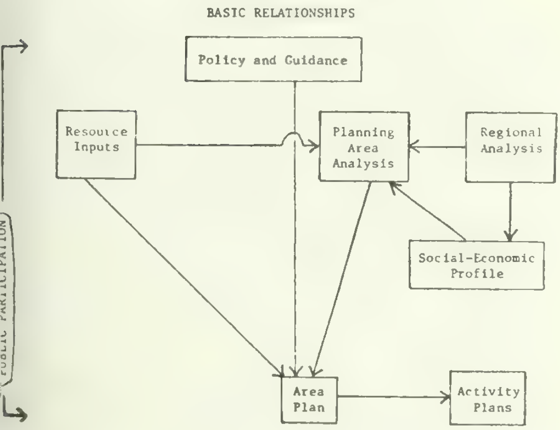
"Planning is essentially the allocation d balancing of resource potentials with source demands within social, political, ological, physical, economic and legislative nstraints." (Barney & Egging 1977)

## WHO DOES PLANNING?

Essentially everyone is involved in the anning process. Some more directly then hers but somewhere along the line everyone ntributes in some manner.

**Most Planning Systems Have Similar Inputs**

**Planning System**



## ALL PLANNING FOLLOWS A SIMILAR FLOW

### General Planning Flow

a - Set objectives
b - Identify issues
c - Gather information
d - Develop Alternatives
e - Selection - decision
f - Feedback and final (adjusted) decision
g - Individual activity plans developed

### What is a Planner?

A planner is a sink for multifunctional information. Each resource function furnishes the planner with data which must be correlated and integrated into a management plan for a specific planning area.

For the purpose of this talk I am going to assume the role of a land planner. I will attempt to discuss some of the types of information which must be acquired and questions which must be raised for fire management to become truly integrated into the total planning process. In the time frame I cannot attempt to be specific on all the information needs. Perhaps I can stimulate a few ideas and raise a few questions.

Fire planning information must be fed into the system at all levels of the planning process. The resource personnel, fire specialist and planners must communicate with each other throughout the planning process. It is not a matter of the planner, as shown on the view graph, asking the fire specialist various questions about the effects of fire on each resource. Fire input data must flow with each resource plan and be considered throughout the entire process. The information must flow as now shown on the view graph.

I will now touch on some planning philosophies concerning fire:

1. Fire behavior can affect the way resources and funds are allocated to reach management objectives. Fire is a factor in production. Fire affects resources in several ways. The most obvious is the loss or modification of the initial resource. This is the effect that we hear the most about. Most people take notice of this initial short-term effect. The planner must consider not only the initial loss but the long-term effect in the area.

The resource damage potential depends upon the resource value and risk of fire. This criteria applies to resources in place and values and risks following planned resource actions.

Example

High value land -- high fire risk

vs

Low value land -- low fire risk

Perhaps in the low value-low risk area the fire effect of a planned action is negligible. Fire is considered and then dismissed. However, in the high value-high risk area a planned action may well change the whole effect of fire. From a funding standpoint the cost of fire presuppression and suppression actions may make the planned resource action prohibitive. If we are willing to accept losses we need to define the costs associated with these losses.

Fire may have an impact on the allocation of resources:

Example

A management plan calls for timber harvesting. This may be completely compatible with the other proposed resource actions. However, from a fire standpoint the amount of slash created is beyond the acceptable limit. Fire personnel can no longer protect the area within acceptable protection standards. The cost of presuppression and suppression may well be prohibitive. Fire can quickly wipe out or drastically change the intent of resource plans. At the same time fire may not have any effect. The main thing is, as planners, we need to know what the effect will be.

Therefore, fire management must enter into the early phases of the planning process, not only as it affects resources in place but also its effect on the allocated-planned resource action.

2. Political Acceptability.

There is a political acceptability factor involved in fire. Not only from wildfire but prescribed fire.

People generally cannot accept the unattractiveness of burned over areas. Whenever we plan prescribed burns we begin to feel the "outside" pressure.

Large wildfires cause a considerable amount of outside public pressure.

A. Perhaps a classic example occurred in Grand Teton National Park a few years ago. Following a management plan, a wildfire was allowed to burn. The supposed resource loss and smoke problems created a political beehive in the town of Jackson, Wyoming, and eventuall nationally.

B. This last fire season a fire burned through Pattee Canyon near Missoula, Montana. Several homes were destroyed. This has create a social-political problem that will be around for a long time.

The political aspect created by fire must be considered in planning.

3. Short Term - Long Term.

Fire has a short-term and a long-term effect. Immediately after a fire it looks completely devastating. However, by the next year the burn area has improved considerably. At the same time the long-term effect may be the real problem. Planners must know what the short and long-term effects will be.

4. On Site - Off Site.

Fire may have an effect off-site as well as on-site. Smoke, drift of particulates, et may cause serious problems downwind from a bu

Also, a burn in a certain area may creat an "ice cream" area for wild or domestic animals. The invasion of above normal numbers o animals into the area may well create problem in adjacent areas.

Example

An area was prescribed burned. Nearby an area had recently been planted with Ponderosa Pine. Following the burn there was a marked increase of browse species. The deer and elk began to congregate in the burn area. As a result the new seedlings in the jacent area were either trampled or snipped f.

Planners must be made aware of these on te - off site interactions.

### 5. Safety

Safety is another aspect which must be nsidered. This is particularly true with the esent urban-forest interface. People are ilding extensively in the "wilds." This is eating a problem which planners cannot ignore.

Example

A small tract sale in Arizona on the upper 3 of a mountain. Beautiful scenery -- back- -nature type living. However, there is only e road and the fuels below the development e explosive. To add to this, forest product les in lower country are creating slash and creasing the problem. Costs of prevention, esuppression and suppression have increased amatically. This increased cost is directly ed to the safety of people.

Again, the on site - off site, long term - ort term interaction of planning actions and re -- planning with tunnel vision.

Safety must be considered in our planning.

One way to ensure that these problems are nsidered is to gather fire data on a proba- lity basis. Not only from the existing re- urce standpoint but from each planned action well.

The information resolution depends upon e level of planning. A broad base may be ne for upper level planning but must be ecific for activity planning.

Planners need to know several things:

- The probable fire occurrence, numbers, cation, time and cause
- The probable weather
- The probable fire size and intensities
- The probable effects of fire on various sources
- External impacts of access, recreation, gging, etc., both short and long term - on te and off site
- Effects of planned actions on suppression
- Effects of planned actions on fire costs
- Effects on probable consequences

Each activity must consider fire. The consequences of all planned actions must be determined. This is the first step. However, we still need to examine the overall interaction of all activities on a planning area. Independently they may be of no consequence, collectively they may be a disaster.

We need to know what alternatives the fire specialist can offer to help achieve management objectives. We also need to know and analyze the effect and cost of these alternatives. We need to know the effect of the alternatives on probable consequences in terms of resource production.

Planning is never complete, it is dynamic and must remain flexible to change. There are no stock answers but we must ask questions. We must challenge the fire specialist to furnish the needed information. We must create an awareness of fire as a modifier of production, either good or bad.

Awareness can only come through the interaction and interplay of fire, resource and planning personnel.

As John McGuire said in a speech in Missoula: "Fire managers must constantly ensure that fire is considered an equal component in forest ecology - along with soil, air, water, land, and life forms. Much of the progress that has been made in fire management will be cancelled out if fire is allowed to become an ecological island separated from the broad body of land use planning."

# HOW FIRE-RELATED ACTIVITIES CAN BE TAILORED TO MEET RESOURCE MANAGEMENT OBJECTIVES

Clinton B. Phillips

Assistant Chief, Fire Protection
California Department of Forestry
Sacramento, California

## INTRODUCTION

Some of you may be like I am: a thick-skinned, hard-of-hearing traditionalist. For many years we fire fighters, fire managers, and resource managers have been bombarded, lambasted and harangued about the need to integrate fire and fire management into plans for managing wildland resources. The two previous speakers have again enunciated what we should be doing. Perhaps it is time we turned up our hearing aids and heeded the call for action.

How do we go about tailoring systems of fire management to meet the objectives of resource management? The answer is simple: It's not easy! But difficult tasks have never deterred us foresters, so let us accept this present challenge.

Before we can proceed to develop a plan of fire management for any given planning unit, we need to do at least four things:

1. Establish objectives for managing the resources.
2. Determine the effects of fire and fire management on the resources and on the objectives for managing them.
3. Determine the effects of various activities of resource management on different strategies of fire management.
4. Develop a procedure for fully integrating a plan of fire management into a multifunctional Grand Plan of Resource Management.

Let us take a broad view of each of these four tasks.

## ESTABLISH OBJECTIVES FOR MANAGING RESOURCES

Probably few of us here today are in the position of actually establishing objectives of resource management. Generally that task is left to the Grand High Moguls and, at least in relation to government-owned lands, to the general public. It is right here, however, in the initial stages of planning a system of resource management, that we fire managers and resource managers must sit around the same table and hammer out a common understanding about the role of fire in the forest.

Fire can be either a scourge or a blessing to man and his resources, depending on how it is managed (Mutch 1972). Uncontrolled, fire can have highly dramatic and modifying effects on wildland resources. Under control, however, fire can be used to serve the objectives of the resources manager. And, because it is a natura element, fire must be used so that its dramatic effects also serve nature (Vogl 1974).

These two principles--the use of fire to serve both man and nature--need not be in conflict. Before they can be applied to the objectives for resource management, however, the net effects of fire upon resources must be determined.

## EFFECTS OF FIRE AND FIRE MANAGEMENT UPON RESOURCES

Wildland ecosystems are extremely complex, and the effects of fire and fire management on those ecosystems are equally complex (Noste and Davis 1975). The effects of fire are a function of many things, including at least th following:

- . . the intensity, rate of spread, location and size of given fires;
- . . the frequency of fires in any one location;
- . . susceptibility of individual resources to different intensities, sizes and frequencies of fires.

Despite its sudden and dramatic impacts, fire is usually selective. It affects individual resources in different ways: sometimes damaging, sometimes beneficial. It is the tot range of effects, which vary according to the characteristics of individual fires and resources, that we are interested in.

Many effects of fire are not yet well understood, which complicates our task of integrati ire into resource management. More and more, owever, the relationships between fire and the roduction of resources are being established hrough research and field observations. A ather thorough summary of these relationships as made recently by the Society of American oresters' Prescribed Burning Task Force (Martin al 1977). Where the effects of fire on re- ources are not known, research still has a ob to do.

To the degree that we can determine the net ffects of fire on resources, we must distin- uish between those fires which help to achieve e objectives of resource management and those ich are counter-productive to the objectives which may pose a threat to man and his en- ironment (Barrows 1974). In other words, we eed to distinguish between "wildfires" and rescribed fires." You may prefer to call ese, respectively, "unwanted fires" or anted fires," or any of several dozen other erms that seem to be used among us fire mana- ers these days.

Where fire is determined to play a necessary d enhancing role, then it should be included the plan for fire management. Certain ightning-caused fires might be allowed to read freely under prescription. Or, as a bstitute practice, fires might be deliber- tely ignited, also under prescription.

Many lightning-caused or man-caused wild- ires are not wanted simply because their net ffects may be contrary to the objectives of esource management or are threatening to human ife and property. These fires must continue be prevented or suppressed! Jim Agee (1974), ecologist with the National Park Service, as said:

> "Some natural category areas protected from fire for many years have high fuel accumulations, which, if ignited, would result in an unnaturally intense fire. These areas must be protected from fire until fuel has been manually removed or prescriptions for burning have been developed."

If the decision is made to suppress unwanted ightning-caused fires, then some alternative ractice must be provided that will resolve at east partially the conflict between man and ature. Prescribed fire should be the first hoice, but only it is is determined to be ost effective and consistent with the objec- ives of resource management.

Now let's look at the effects of resource anagement on fire management.

## EFFECTS OF RESOURCE MANAGEMENT ON FIRE MANAGEMENT

Each function of resource management, including fire management, must take a look at what impacts all the other functional plans might have on theirs. The plan for forest silviculture, for example, may call for thinning of young-growth trees with no specific provision for disposing of the fire-hazardous slash; such a plan would impact importantly on the plan for fire management. The plan for reforestation may call for valuable investments of both dollars and time; without adequate provision for protecting the young trees, the investments may disappear in a scintillating flash through the wizardry of wildfire (Wilson 1977).

This interplay among the many functions that serve resource management is a very difficult game to play. It requires maximum patience, coordination, understanding, and compromise.

Having done our homework, let's try to pull all our data and information together into a plan of fuel management.

## A SUGGESTED PROCEDURE FOR DEVELOPING A PLAN OF FIRE MANAGEMENT

Figure 1 is a procedural model that could be used to integrate fire management into broad plans of resource management. Each step in the model actually has a complex sub-system of its own. Let's take a look at each of these steps without getting into too much detail concerning the sub-systems.

The purpose of Step 1 is to establish objectives for a plan of resource management. Since fire plays a role in virtually every wildland ecosystem, it must be considered in this first stage of planning. One of the best guidelines to use for this purpose is the U.S. Forest Service's booklet, "Fire Management Considerations for Land Use Planning" (Anonymous 1974).

The purpose of Step 2 is to assess the current fire situation for the management unit with which we are concerned:

1. History of fires and their effects on the resources being managed.
2. Sources of fire risk.
3. Expected fire behavior - dependent on fuels, weather and topography.
4. Worst probable fire situations.
5. System of fire management and protection provided at present.

These data and bits of information are used in Step 3, where the effects of fire on

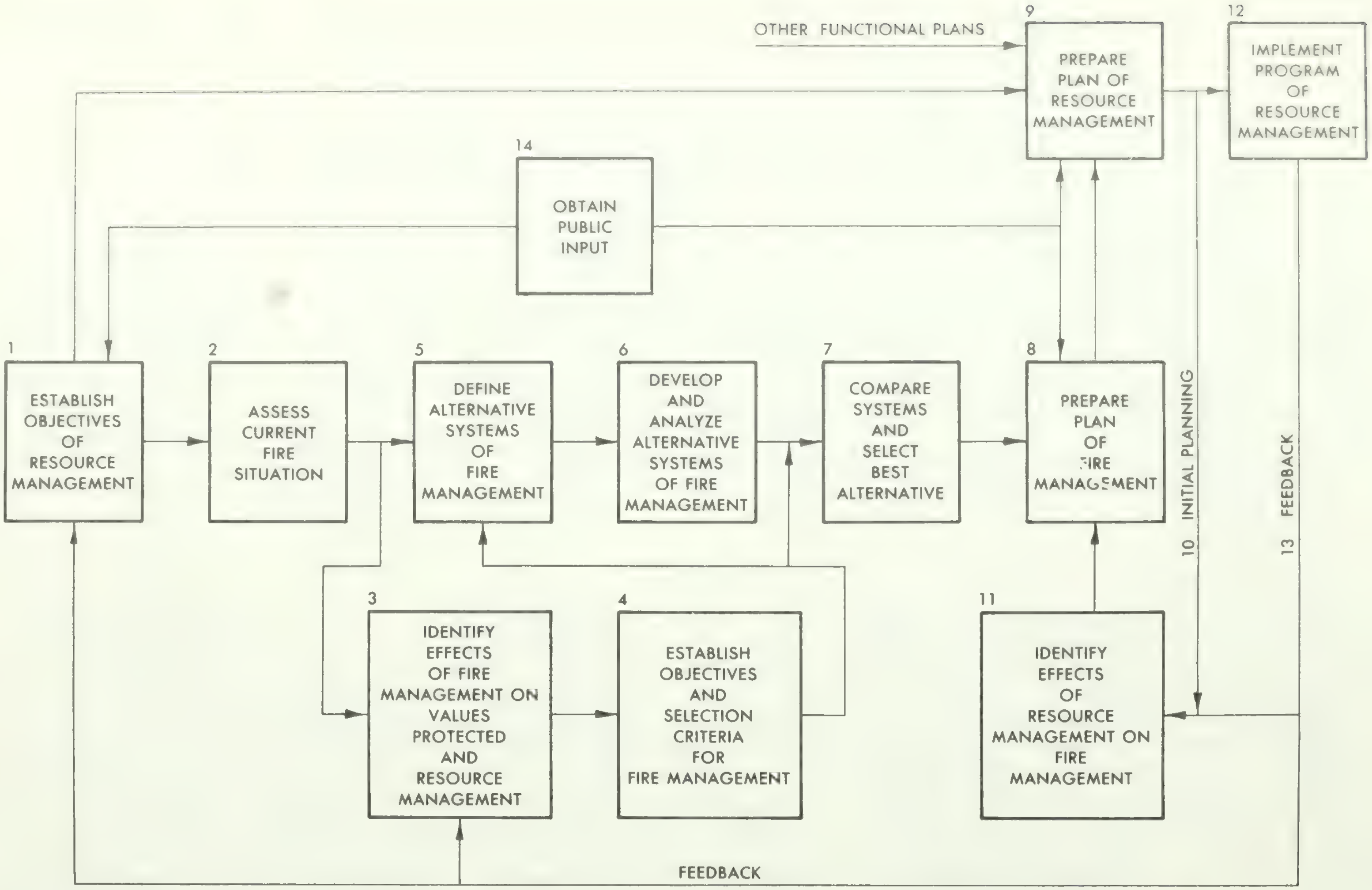

OTHER FUNCTIONAL PLANS
1 ESTABLISH OBJECTIVES OF RESOURCE MANAGEMENT
2 ASSESS CURRENT FIRE SITUATION
3 IDENTIFY EFFECTS OF FIRE MANAGEMENT ON VALUES PROTECTED AND RESOURCE MANAGEMENT
4 ESTABLISH OBJECTIVES AND SELECTION CRITERIA FOR FIRE MANAGEMENT
5 DEFINE ALTERNATIVE SYSTEMS OF FIRE MANAGEMENT
6 DEVELOP AND ANALYZE ALTERNATIVE SYSTEMS OF FIRE MANAGEMENT
7 COMPARE SYSTEMS AND SELECT BEST ALTERNATIVE
8 PREPARE PLAN OF FIRE MANAGEMENT
9 PREPARE PLAN OF RESOURCE MANAGEMENT
10 INITIAL PLANNING
11 IDENTIFY EFFECTS OF RESOURCE MANAGEMENT ON FIRE MANAGEMENT
12 IMPLEMENT PROGRAM OF RESOURCE MANAGEMENT
13 FEEDBACK
14 OBTAIN PUBLIC INPUT
FEEDBACK

FIGURE 1. MODEL FOR INTEGRATING FIRE MANAGEMENT INTO RESOURCE MANAGEMENT.

urces are assessed, and in Step 5, where epts are defined for planning alternative ems of fire management.

he purpose of Step 3 in the model is to tify or predict the net effects of fire fire management on resource values and on objectives of resource management. The effects lead us to the definition of "values ected," i.e., that value of each resource h could be damaged or destroyed by the est intensity of fire likely to occur within planning unit (Noste and Davis 1975). The ure of "values protected" provides one of more important elements for planning a em of fire management.

he purpose of Step 4 is to establish the ctives of fire management which will help eve the objectives of resource management. , based upon these objectives, criteria are cted against which alternative systems of management will be compared in Step 7 to ct the "best" system.

he objectives will tell us what it is we nd to achieve within a specified time period. objectives are independent of the means of mplishing them, and, at this stage of plan- , they are also independent of the cost. might take on forms something like the owing:

llow each lightning-caused fire to urn freely so long as it is not hreatening to spread beyond the ounds of the planning unit, and s not threatening human life or roperty.

uppress all wildfires as quickly s possible within the Brown's Ra- ine planning unit.

he selection criteria are established for purpose of achieving the objectives. They ie the alternative systems of fire manage- developed in Step 6 to be compared for the ose of identifying how well each alternative sfies the objectives. Therefore, at least selection criterion must be established each objective. For example, an objective t be to burn stands of predominately ponder- pine at least once every 10 years. For objective, a selection criterion might be elect the system of fire management which d minimize ecological damage to the habitat he Three-toed Hairy-chested Salamander; or h would minimize smoke over the community rown's Ravine; or which would maximize com- bility with cooperators.

f Step 4 is performed with care and insight, it should result in a thoroughly satisfactory system of fire management.

The purpose of Step 5 is to define alternative systems of fire management which will satisfy both the current fire situation and the objectives established in Step 4. The systems defined in this step will be further developed and analyzed in Step 6.

At least three alternatives should be defined, and preferably more:

1. The current system
2. The baseline system which is an extension of the current system
3. One or more additional systems which may be major departures from the current system.

Each alternative is described in narrative form with regard to general fire protection philosophy; prevention; detection; suppression; fuel management including the use of prescribed fire; interagency relationships; fire laws, regulations and codes; and support functions.

Each system is then compared to the objectives to assure that the objectives are met. The current system may or may not meet all objectives, but the baseline system and all other alternative systems must meet all objectives for all time periods.

The baseline system is basically the same program of fire management as the current system but with modifications to personnel, equipment, and facilities needed to meet both the current fire situation and the objectives established for the new system. One modification, for example, might be to increase the response on fire engines from three to five fire fighters.

The additional alternatives should incorporate as many new or different ways as possible of providing a system of fire management. By challenging tradition, much better and more cost-effective ways of fire management may be found for meeting the objectives of resource management. DESCON is an example of such an alternative (Jay 1976). Another alternative might be to shift emphasis from suppression to prevention by establishing more "greenbelts" to separate wildlands from urban environments.

The purpose of Step 6 is to develop further the alternative systems of fire management defined in Step 5 and to analyze them relative to a set of critical factors.

The further development of the alternatives involves identifying the organizational functions and the resources needed to perform the functions. Let us examine just one example: prevention. Sub-functions of fire prevention might include education, law enforcement and engineering. Tasks to accomplish these subfunctions would include such things as inspections, investigations of fires, and analysis of data. The tasks would be further translated into numbers and types of personnel, equipment, facilities and materials needed to carry out the function of fire prevention.

Each alternative system of fire management would then be analyzed in terms of cost, benefit, legislative acceptance, political acceptance, ecological consequences, and other critical factors. Several powerful mathematical and modeling techniques have been developed in recent years for making analyses of these kinds.[1] FOCUS (Fire Operational Characteristics Using Simulation) is one modeling technique that is being used operationally by several federal and state agencies to compare suppression alternatives against a given set of data (Phoenix 1976).

The purpose of Step 7 is to compare the alternative systems of fire management and to select the best alternative. The alternatives are ranked in relation to the critical factors of analysis used in Step 6: Cost, benefit, etc. They are also ranked in relation to the selection criteria developed in Step 4. Again, any one of several analytical techniques can be used in making the rankings.

The "best" alternative system of fire management is the one with the greatest total of weighted rankings. If we have used care and thought in establishing our selection criteria, priorities, and weightings of various values, and if we have used the best available information in comparing the alternatives relative to the various factors of analysis, then we should have confidence in our final selection.

The purpose of Step 8 is to develop further the best system of fire management selected in Step 7. The task in this step is to fill in the details of the plan so that it can be fully integrated into the plan being prepared for resource management. The plan should not be static for any period longer than one year and preferably less. It must be a continuous, dynamic, evolving plan intended to meet constant changes in (1) the needs for fire management, (2) the people's expectations and willingness to pay and (3) the technical capabilities of fire management (Phillips 1976).

Using principles of master planning, the plan of fire management might note who or what agency is to perform specific functions in what particular manner, and by what period of time in order to best accomplish objectives of both fire management and resource management. Not all functions need be performed by the responsible fire management agency. For a number of reasons--cost-effectiveness, expertise, the desirability of having a broad base of participation--it might be best that some functions be performed by other public or private agencies.

By now we should have a well-conceived plan of fire management, nicely packaged, and ready for presentation to the Grand High Moguls of Resource Management. Let us move onward with heads held high!

The purpose of Step 9 is to prepare a plan of resource management which uses the techniques of systems analysis to bring together a whole series of subsidiary plans, including a plan of fire management. Hopefully, we have done a good job of interfacing and coordinating our planning with other functions having inputs to resource management. But not until all the various functional plans are meshed into one Grand Plan of Resource Management can we accomplish the feedback shown in Steps 10 and 11 in our model.

Finally, there is a plan of fire management-which is good only for the moment, since changes are already occurring out there in the real world which will require changes in our plan of fire management. Step 13 is another feedback which recognizes this continual change and provides for it.

In keeping with this convention's theme of "Forests for People," the purpose of Step 14 is to insure that the public is given the opportunity to hear and comment upon the plans of the agencies that serve them. To paraphrase the Scottish poet Robert Burns, "The best-laid plans of mice and bureaucracies often go astray if the ordinary citizen doesn't understand or agree with them." You can select from your own local experiences to illustrate that observation

## CONSTRAINTS TO FIRE MANAGEMENT

Unfortunately, there are some important constraints to integrating fire management into resource management (Moore 1974). Here are just a few of them: Inadequate knowledge about fire management; the need to convert present knowledge into improved operational guidelines; the need for more training in the professional and technical aspects of using prescribed fire;

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[1] R. Benjamin. 1977. Policy analysis factors. Lecture given at the interagency course on advance fire management, Marana, Ariz.

anging social values and patterns of land
nership; the fact that most state fire pro-
ction agencies have no legal authority to
ply prescribed fire to privately owned land;
ability for damages incurred by adjacent
ndowners as the result of escaped fires; the
ct that a fixed-level budget may prevent
re managers from meeting stated objectives
d enable them only to plan for the best
location of available funds and resources;
lack of agreement among fire managers on
rminology; and the fact that few universities
d colleges include much fire management in
eir professional forestry courses.

## CONCLUSION

Despite these and other constraints, good
ings are happening nationwide that should
rmit us to move ahead more swiftly in the
anning of systems of fire management and
re protection. Among them are: (1) the
re in Multiple-Use Management Project at
e Northern Forest Fire Laboratory; (2) the
re Management Planning and Economics Project
the Riverside Forest Fire Laboratory;
) the Interagency Fire Planning Working Team
the National Wildfire Coordinating Working
oup; and (4) the Interagency Course in
vanced Fire Management.

Hopefully, these new developments and this
chnical session will help to bring us closer
gether in realizing both the need and the way
r integrating fire management into plans for
source management. I invite you to join
--one of the long-time traditionalists--in
quest for more imaginative and more effective
ys of protecting and enhancing wildland re-
urces through fire management. Let us stride
rward with confidence!

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# Simulation--A Thinking Tool

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and
Systems Analyst, Northern Forest Fire Laboratory,
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Today, natural resource managers and scientists are required to evaluate and even anticipate the effects that management practices for a single resource will have on the production or use of all other natural resources. For example, a successful prescribed fire will accomplish the management objective for thinning and maintaining the desired stand age-structure. However, it is difficult to quantitatively evaluate the effects of the fire on wildlife habitat structure, forage and browse production, water yield, erosion, and recreation. After a fire, how long will it be before production of the other resources is restored or stabilized? If the fire were prescribed for a different time in the year, would the effects be the same? What would be the effects of a fire with a different intensity? Are some of the effects on the other natural resources in the ecosystem dependent on how long ago the same area was burned? If the same area were burned again 10 years from now, what would be the stage of plant and animal succession? Questions such as these and many more must be the concern of the forest manager. With so many factors, conditions, interrelationships, and variables involved in judging the effects of fire on a specific ecosystem, it is extremely difficult to be sure "all bases are covered."

Today, as in the past, judging the effects of a fire on other resources in the ecosystem was done through the experience of the manager. Experience takes time, is often confined to particular forest and climatic types, and is usually non-transferable--either to different forests or foresters! Collectively, the experience of managers and the results of research in the western United States probably represent the answers to 80% or 90% of the questions we need answers to. Why we do not have these answers when we need them is due to many reasons--ignorance, fragmental data, incomplete studies, (seemingly) unrelated studies, unpublished reports, thousands of individual studies that have not been summarized or synthesized, time--to name a few. Usually, such an unorganized state of our knowledge leaves us with little usefulness.

Can our knowledge of fire effects be organized to be more useful? The systems approach is a procedure worth considering. It is nothing more than the systematic organization of knowledge that explicitly recognizes the interrelations that are important for us to know for our purposes. Depending on our needs, a systems approach may result in economies of knowledge like a taxonomic key of tree species. A systems approach to a more dynamic problem may result in a computer program for projecting timber volume and growth for an all-age stand. Such "information rich" results of a systems approach are called models. Models represent the important details of the real world. They are much simpler than the real world and exclude many details we choose to omit or ignore.

The two examples we have mentioned, the taxonomic key and the computer program for predicting timber volume and growth, represent two basically different kinds of models. The taxonomic key is an example of a static model, and the volume-growth computer program is an example of a dynamic model.

The taxonomic key is a model of the essential features of tree species that are necessary to distinguish between similar trees. The economy of knowledge comes from reducing all the possible characteristics of the trees to a smaller number of important features that will consistently differentiate a given species from all the rest of the trees in the key. The taxonomic key is a static model because, once developed, the interrelationships in the key do not change. A topographic relief model of a watershed is another example of a static model.

The computer program for projecting future growth and volume of a timber stand is an example of a dynamic model. Dynamic models incorporate the mechanisms of how changes occur in the system, i.e., growth and volume of trees in different age (size) classes and the continuously changing volume in the different age classes. With dynamic models, we are able to "see the system in motion." Examples of other dynamic models include hydrologic models, wildlife population models, and photosynthesis models.

A model airplane is a common example used to illustrate the difference between static and dynamic models. If the purpose of modeling an airplane is to display a miniature on our desk, the model is static. If the purpose is to build a model to fly by remote control, we must include an engine and mechanisms to accomplish maneuvers, i.e., flaps, elevators, rudders, and a remote-control radio.

Some objects or phenomena (like the airplane example) can be modeled using mechanical or electronic relations. Others, because of their complexity, must be modeled by using mathematical or logical relations. In these cases, it is necessary to be able to write equations or logical sequences that simulate the behavior in response to changes we wish to impose or assume.

## MANAGEMENT-ORIENTED SIMULATION MODELS

The wildland manager is faced with the problem of simultaneously managing a multiple resource base. The public manager is directed by law to manage for the multiple use and sustained yield of these resources (the Multiple Use-Sustained Yield Act, PL 86-517). In managing a land area, no resource or use can be isolated. Any management action, even when directed at one resource, is going to have an effect on the other resources of the area and the possible uses of those resources.

A logging operation started in any forest will affect not only the timber resource, but also the water, forage, and wildlife resources. This interaction can be illustrated as in Fig. 1 (Egging 1977a). For this reason the overall area with all its resources must be viewed as a whole in making any management decisions on a proposed activity.

Recognizing that man's activities impact the interrelationships of the ecosystem components, Congress passed the National Environmental Policy Act in 1968. This Act directs the land manager to assess his management activities from an environmental impact standpoint. The Act declared it "a national policy [to] encourage productive and enjoyable harmony between man and his environment; [and] to promote efforts which will prevent or eliminate damage to the environment" (USDA Forest Service 1974:243). "This policy is one of balancing the amenities or quality of life against the continued use of renewable resources" (Leopold 1975:609). By this act the manager must prepare a detailed statement of the environmental impacts of any proposed action that might have an effect on the quality of the human environment. These impacts must include not only the short-term immediate effects, but also the long range effects of the activity.

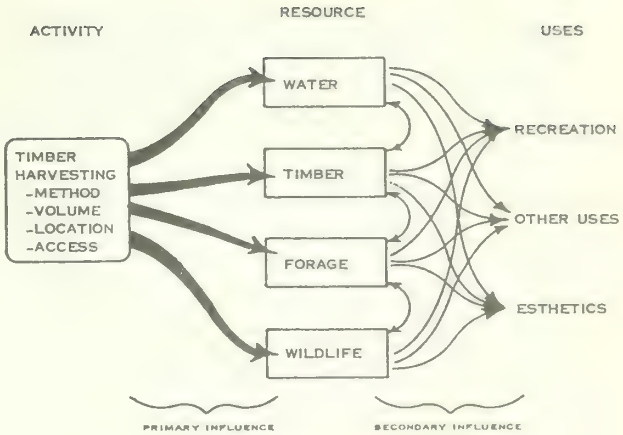

Figure 1.--The influence of timber harvesting activity on resources and uses

As an example of man's activities impacting the ecosystem, we might look at the timber harvesting example illustrated in Fig. 1. The harvesting of timber from a given area and the method used in harvesting will have a direct effect on the area's resources: water quality and quantity, timber availability now and in the future, forage quality and quantity, and the amount and type of wildlife present. These can be both short and long range effects.

In addition to these primary effects, the changes in available resources will cause a change in the possible uses of the area. The recreational appeal and aesthetics of the area will be influenced secondarily. There are also secondary influences between resources, that is, a change in water quality might affect fish populations. A change in the timber or vegetation will cause a change in the water quality and quantity. It can also cause a change in the wildlife of the area.

Fire is a natural force which will impact the resource system in a similar manner. Fire removes vegetation from the system. This vegetation can be either live or dead. It removes timber from the growing stock; it exposes mineral soil to the ravages of wind and rain, increasing soil erosion. On the other hand , fire also acts as a rejuvenator; it promotes species diversity; it can remove ground cover to accept seed for regeneration; it can promote browse and forage production. Fire is a production factor in the wildland ecosystem. The "goodness" or "badness" of any of these consequences can only be judged relative to the management objectives established for the area.

The ecosystem we are managing is a maze of complex interacting cause-and-effect relationships. This complexity makes multiple use management with the evaluation of environmental consequences difficult to practice in a real-world situation. The resources of an area and the uses of those resources are affected over a considerable time period when a particular impact or activity is imposed on the system. These impacts must be projected and evaluated before an activity is started. Activity strategies must be compared to pick the most desirable strategy in meeting public demands and management objectives.

Modeling and simulation is a tool which can help the manager project consequences into the future. The dynamic responses of the ecosystem can be presented in comparing alternatives over extended time periods. Simulation can help clarify the manager's thinking and can be a valuable tool in his decision making.

## SIMULATING FIRE

The land manager must make decisions on which course of action is most desirable in a given situation. Simulation is a valuable tool to help in analyzing the consequences of a proposed strategy. With fire the basic decision facing the manager is one of balancing the trade-offs between fire use and fire control. From a modeling standpoint this might be illustrated as in Fig. 2.[1]

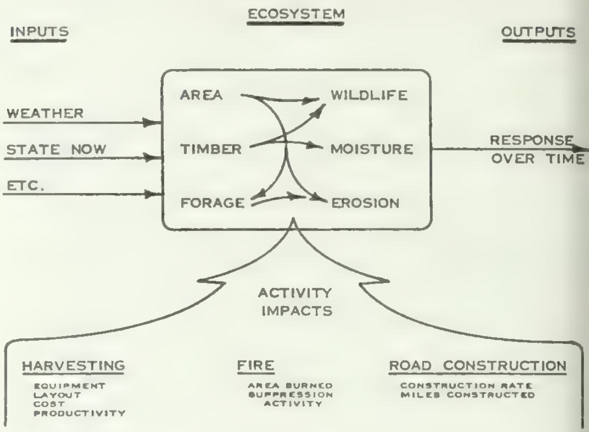

Figure 2.--Black box diagram of ecosystem response to activity impacts

Shown is a diagram of the ecosystem with its inputs and outputs. The inputs to the system include such things as weather and the state or condition of various resources of the area as they exist now. The model is then subjected to some form of external impact; be it timber harvesting, fire under a given strategy, or road construction. The ecosystem model is allowed to respond through its internal interactions to provide the output in the form of resource and environmental response over time.

As mentioned before the decision relative to fire is basically one of balancing the fire use and fire control strategy for a given land area. The information flow for a fire management decision process might be illustrated as in Fig. 3.[2] To build such a system there are basically three components for information processing: fire behavior, fire effects, and economic evaluation. Each

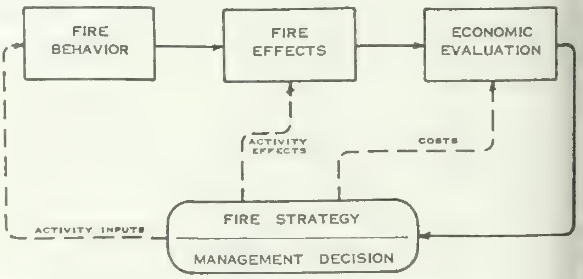

Figure 3.--Information flow for fire management decision system.

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[1] Egging, L. T. 1977a. Systems and simulation in natural resource planning. Manuscript in preparation.

[2] Egging, L. T. 1977b. Integrating fire int land management planning: A perspective. Manuscript in preparation.

of these may be thought of as a model to represent some phase of the real situation.

Much work had been done to improve fire behavior modeling. The National Fire Danger Rating system attests to this fact (Deeming et al. 1974). The work by Rothermel (1972) has contributed to the increased capability in modeling fire spread in wildland fuels and the work of Albini (1976) in estimating wildfire behavior. However, this work is only a beginning in the development of fire management decision system. The outputs from this behavior modeling effort must be coupled with fire effects models. This effort might be diagramed as in Fig. 4.

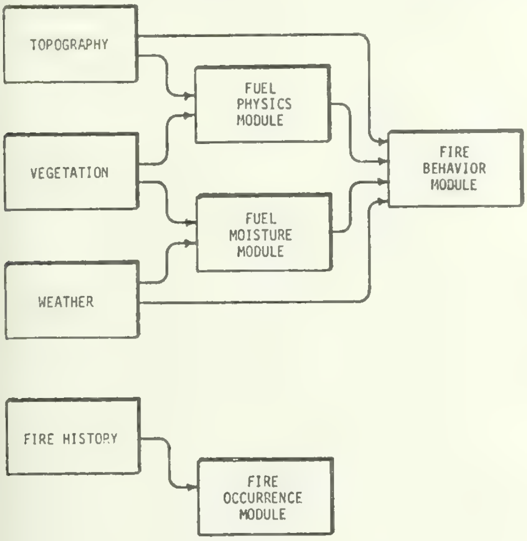

Figure 4.--Fire behavior system.

First, we must be able to describe the on-the-ground situation in terms required for modeling fire behavior. This description includes such things as topography, vegetation, fuel inventory, and weather. This information, in turn, is utilized to describe the fuels situation from both a physical standpoint and its moisture characteristics. All of this information is utilized by the fire behavior model to predict such fire attributes as rate of spread, intensity, and duration.

This leads us to the next phase of our fire management decision system. Namely, the fire effects models. We must now convert the fire behavior information into terms meaningful for evaluating the ecosystem response with respect to the management objectives. This can be done by simulating the response of resources over time to fire effects. The components of this modeling effort can be broken down as shown in Fig. 5. For example, we may look at the primary effects of fire on soils, vegetation, and air quality. Air quality is something that becomes more and more important when we start looking at prescribed burning strategies over large areas. It is one important factor that should be included in any fire effects modeling effort. Following these primary effects of fire we can now start looking at the ecosystem response to the fire impact. This response can be expressed in terms of changes in resources or resource production over extended time periods. It also includes the environmental consequences of the fire impact over time.

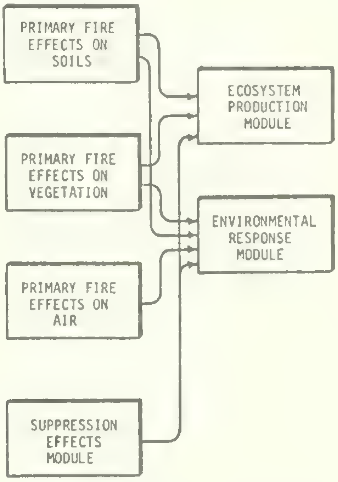
PRIMARY FIRE EFFECTS ON SOILS
ECOSYSTEM PRODUCTION MODULE
PRIMARY FIRE EFFECTS ON VEGETATION
ENVIRONMENTAL RESPONSE MODULE
PRIMARY FIRE EFFECTS ON AIR
SUPPRESSION EFFECTS MODULE

Figure 5.--Fire effects system.

These consequences can be simulated to give projections of resources such as illustrated in Fig. 6 (Egging 1977a). Such an illustration shows the interactions between resources. The environmental consequences of the impact and subsequent management activity can also be represented.

This information is then utilized as a basis for making an economic evaluation of the strategy under consideration. The economic evaluation model can be diagramed as in Fig. 7. It consists of three basic components. The first is an evaluation of changes in resource production. The second is an evaluation of the environmental consequences, such as air quality, and erosion. Finally, the consequences of the strategy in terms of production and environmental factors are evaluated as to how well they meet the performance criteria established in the management objective.

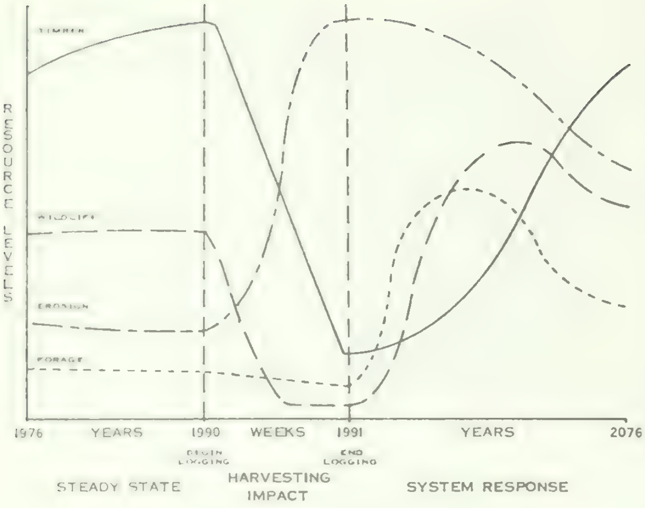

Figure 6.--Hypothetical example of ecosystem response to impact.

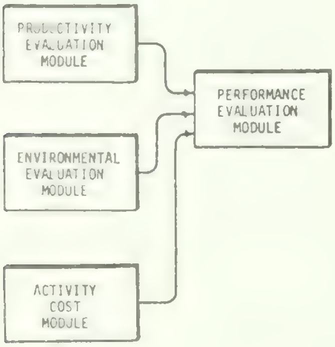
PRODUCTIVITY EVALUATION MODULE
ENVIRONMENTAL EVALUATION MODULE
ACTIVITY COST MODULE
PERFORMANCE EVALUATION MODULE

Figure 7.--Economic evaluation system.

Multi-resource simulation models can provide the resource manager with a powerful thinking tool for evaluating the consequences of the alternate management practices he has at his disposal. However, such management-oriented models must prove to be more useful than the judgment based on the manager's own experience before they will be used.

To be actively employed by managers, simulation models must have user-dedication. To accomplish this, the model must be designed by managers with respect to the kinds of questions to which he is seeking answers, the effects of specific management practices over which he has control, the form of the output of the model in terms of tables and graphs, and the units of the output the manager is used to working in. In addition, the input needed to operate the model must b that which is available to the manager.

Of the hundreds of models built for managers, few receive dedicated use because the managers were not involved in the buildi of the model. We believe that models can serve as useful thinking tools for managers if managers actively participate in the beginning stages of modeling and throughout the model development. User-dedication of models will come only through user-involveme in their construction.

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FIRE WORKING GROUP

# CURRENT TRENDS IN LEGISLATION AFFECTING FOREST PRACTICES RELATED TO FIRE: SESSION SUMMARY.

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"The first step in forest management is rotection from fire" is the axiom we've work- d with for the past sixty-five years. The eeks Act of 1911 started us in the right di- ection and was followed by the Clarke-McNary aw (CM-2) in 1924. The results have been pectacular in that as late as 1940, 30 million cres were being burned annually. These losses ave been reduced to 10% of that figure.

In talking about legislation we should lso talk about funding. The Clarke-McNary aw allows the federal government to contribute to 50% of the total cost of fire protection xperienced in the states. Until 1978, the gh point had been reached in 1974 when 25 illion dollars had been granted. For several ears after 1974 the administration demanded imination of all funding for CM-2. The nding levels granted by Congress for the riod 1975-77 were $22.6 million, $20.6 million d $18.6 million, respectively. A combination changing attitudes in the Congress combined th the implementation of the RPA Act has en a dramatic rise in the federal funding are to $30 million in 1978. With these funds, re management, as we consider it today, can come a reality. Whereas for the past 4 or 5 ars fire organizations have been experiencing trenchment, the funds should now become ailable to implement the fire management tool.

Other laws have had an impact on the olution of fire management. The Wilderness t of 1964 has been interpreted by many as e device which introduced the "let burn" licy. It should be remembered, however, at fire control is not excluded by the lderness Act. It does allow, however, for conscious decision to allow a fire to burn the benefits exceed costs.

The National Environmental Policy Act 1969 (NEPA) provided the mechanism for determining environmental impacts, and involvement of the public in decision making often resulting in challenges regarding fire exclusion. The filing of environmental impact statements has led to modeling systems for decision making.

The Clean Air Acts, while admirable, are leading to conflicts between state air pollution authorities and others, particularly forestry agencies. For example in the State of Montana the air pollution authority is endeavoring to eliminate slash burning and the burning of irrigation ditches. It is also anticipated that home fireplaces will be regulated. This is as it should be since visible air pollution from this source can be dramatic in areas affected by inversion layers. Oftentimes, in such instances, breathing can become difficult.

In the Willamette Valley of Oregon, grass growers are being limited to a ceratin number of acres burned annually; these acreage allotments are being reduced. Farmers are being told to find other ways to substitute for fire. Smoke is so serious, the Southern Fire Laboratory at Macon, Georgia is devoting almost full time to smoke management research. In the south, managed fire is a key tool in forest management. It must not be lost.

The Forest and Range Land Renewable Natural Resources Planning Act of 1974 (RPA) is forcing "people" to question current policies and procedures of fire control organizations; for example: the 10 AM control policy.

Finally, the National Forest Management Act of 1976 will lead to decisions on the use of fire in fuel treatment, timber stand improvement and slash disposal. Just how this Act will affect fire management remains to be seen.

Turning to the states, some of the relevant legislation can be broadly categorized into two groups. The first one is the state forestry enabling legislation within each state and the related wildland fire protection authorities and laws that individual state legislatures have provided to deal with their local problems. Not one state is lacking in some sort of legislation regarding wildland fire and fire protection; this couldn't be said 15 or 20 years ago. More recently, mostly in the decade of the seventies, several state legislatures passed legislation in land use planning which directly or indirectly affected land management, fire planning and the fire protection job of state and local governments. Examples of this are the California legislation of 1971 with regards to zoning and subdivisions in new road building practices and Colorado's Senate Bill 35 which requires the State Forester to review all new subdivisions and House Bill 1041 requiring the State Forest Service to fire hazard map the forest and wild lands of the State. Some of the state laws are heavily directed toward state forestry organizations and some are directed toward counties and municipalities. Like the basic state forestry legislation, it is going to take a long time before the majority of the states have desirable laws or practices, integrating land use planning and fire management programs.

A question often asked is, "What does the public seem to want?" Is there any one particular public? There are many publics wanting many different things with regard to forest land management, fire and fire management. Many of those publics conflict in their wants and desires. Some of the staunchest "preservationist" groups are opposed in their views of wanting fire to either be controlled or not in wilderness areas. What does the public seem to want? We should try to find out what the various publics want. Then the job becomes one of integrating those various wants into programs that are acceptable to most publics, hopefully all.

Where are we headed professionally? We are climbing onto higher and higher levels of thinking and plateaus. No longer are we acting blindly on imposed, often self-imposed policies. More and more foresters and fire fighters are questioning policies. They're looking at the environment versus the impacts of fire on a site and are questioning the need for certain kinds of management and fire control techniques. The past 6 to 7 years in our nation's history have seen greater integration of fire into the total land management package. Fire is one of the driving forces at our disposal in manipulating and managing forest cover for whatever benefit we desire. From the legal standpoint, it is questionable whether or not we as a profession can meet the various deadlines legally imposed upon us and still do a quality job. Good land management and good fire management must be predicated on a well-financed, well-equipped, well-trained fire suppression force to keep fire out of the woods when it is not needed. That's basic, and we should not lose sight of that particular foundation block that has taken 50, 60 or 70 years to establish.

What are the weaknesses in the current systems? Policies need to be thoroughly reviewed and clarified. An example again is the 10 AM fire control policy. Then, too, certain agencies should review their policies requiring every fire to have a fire line built around it. Some Alaska lands don't tolerate that kind of thing and a cold trail black line is certainly more environmentally sound than the bulldozer line. Many of our fire control and fire suppression policies in the past have been simple, easy solutions and as such have not always been correct. Each needs to be thoroughly investigated and re-evaluated in the next 3 to 5 years. Further, conflicting legislation needs resolution. Slash disposal laws and pollution standards are at odds.

Where should we be going? It seems reasonable to suggest we try to avoid additional federal laws; modification of some of the present laws may be in order. State legislation is something else. It seems perfectly reasonable to suggest that the Society of American Foresters develop model laws for implementation by the states.

There is a need to address the liability problem locally. It's no secret that an unwanted fire on adjacent forest land owners leaves the burning authority open to litigation.

We as foresters need to communicate fire research needs better. A recent regional conference on research needs listed the research needs in priority order for forest and range lands. Fire related research was far down the list of needs.

This fire working group should take command and lead the way in fulfilling the various needs outlined in this paper. Chapters and Sections could be the instigators of state laws, state and county regulations. Earlier in this fire working group meeting, we discussed definitions for fire management, wildfire and prescribed fire. You came to no conclusion except the possibility that some other groups of foresters or fire fighters would solve these problems of definition. It is your job, working through the SAF, to make these decisions. If you don't perhaps the U.S. Department of Commerce will!

## SUMMARY OF THE SESSION

In combination, the papers presented his afternoon comprise a basic course in ire management. The session started with efinitions of terms, a discussion of the eeds, problems and the benefits of using ire as a management tool. In two short ours, we moved from this to modeling and imulation.

Dr. Rupert Cutler commented on many of he basics in fire management, indicated ontinued and possible expansion of the federal ole in land use planning. Fire will become credible tool depending upon our ability to ope with public attitudes. In short, fire scapes and higher than planned heat intensiies must be kept to a minimum.

Bill Lyon quoted an excellent definition f land use planning as follows, "Planning is ssentially the allocation and balancing of esource potentials with resource demands ithin social, political, biological, physical, conomic and legislative constraints." He tlined for us a planning system in following e basic relationships, emphasizing public rticipation. Planning philosophies were iscussed in such areas as long term -short rm, on site - off site, and so forth. Also own and discussed were the probabilities, pacts and effects which the planner must ow to assure consideration of the philosophies.

Clint Phillips gave the audience the ur prerequisites to be considered before velopment of a plan for fire management: ) Establish objectives for managing sources; (2) Effects of fire and fire nagement upon resources; (3) Effects of source management on fire management; (4) ggested procedure for developing a plan of re management.

He introduced us to a model for integratg fire management into resource management nsidering the various objectives, assessments, iteria, alternatives, comparisons and plans. concluded with a key philosophical comment ich states, "The fact is well established at fire has played some role in virtually ery ecosystem we manage today. It is important d logical that the role of fire be recognized the process of preparing alternatives for naging resources."

Freeman Smith and Louis Egging introduced ny of us to the use of simulation in the deling process. They pointed out the needs ich include the difficulty to quantitatively aluate the effects of fire on wildlife habitat ructure, forage production, water yield, osion and recreation. Further, in the past, judging the effects of fire has been done through experience. Collectively, 80% to 90% of the answers to questions regarding fire management are known. Synthesizing these answers is a basic need. As a solution our familiarity with the taxonomic key of tree species was identified as a static system. On this basis of understanding they built an understanding of a systems approach resulting in a computer program, a dynamic model.

To many of us "simulation" and "modeling" can be classified as "mumbo-jumbo". Fortunately, an illustration was used which bears repeating here.

> A model airplane is a common example used to illustrate the difference between static and dynamic models. If the purpose of modeling an airplane is to display a miniature on a desk, the model is static. If the purpose is to build a model to fly by remote control, we must include an engine and mechanisms to accomplish maneuvers, i.e. flaps, elevators, rudders and a remote control radio.

To those people in the modeling business this illustration is common. For those of us outside the discipline, it is the kind of device we need to more fully understand the concept.

Over the years many foresters and other land managers have realized that dynamic models for timber harvest and volumes are available and of value in managing resources. Smith and Egging pointed out how this model can be expanded to include fire management.

In conclusion, fire management offers one of the most efficient, economical tools in developing and maintaining healthy, viable, productive forests. Utilization of the information presented at this meeting should help in implementation of fire management and an understanding of the principles by not only fellow foresters and land managers but the public as a whole.

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1979. Proceedings of Fire Working Group, Society of American Foresters National Convention, Albuquerque, New Mexico, October 4, 1977. **USDA For. Serv. Gen. Tech. Rep. INT-49, 20 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.**

A compilation of papers presented at the Society of American Foresters, Fire Working Group Technical Session, Albuquerque, N. Mex., Oct. 2-6, 1977. Keynote address by Dr. M. Rupert Cutler, Assistant Secretary of Agriculture, dealt with the session's theme, the relationship of fire to land management. Subsequent papers discussed fire information required by land managers, how fire-related activities can be adapted to land management, using simulation as a planning tool, and legislation affecting use of fire in forestry practices.

KEYWORDS: fire, fire management, land management, planning.

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# UNEVEN-AGED FOREST MANAGEMENT:
## State of the Art (or Science?)

David W. Hann
B. Bruce Bare

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and
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# RESEARCH SUMMARY

Examines some important historical factors that have caused widespread preference of the even-aged management system over the uneven-aged. Major decisions facing forest managers interested in applying uneven-aged management are defined and a review is made of techniques traditionally used, or recently proposed, for use in making these decisions. Finally, problem areas needing further research and development are identified.

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# THE ROLE OF MANAGEMENT AND SILVICULTURE

Over the centuries, two often conflicting forest management systems--even- and ieven-aged management--have been applied to forests throughout the world. Histori- ally, both systems are rooted in the principles of silviculture, but have been expanded include forest management objectives and the organization of the forest property. day, we recognize silviculture and management as separate but related disciplines. lviculture concentrates on the establishment, tending, and harvesting of forest stands ad management focuses on decisionmaking, organization, administration, planning, and ntrol of operations on a forest property to best achieve specified objectives.

Silvicultural systems are classified either as even- or uneven-aged depending rimarily upon the type of harvest-regeneration method employed. Stands containing ees of about the same age that develop under full-light conditions without significant rder competition are silviculturally classified as even-aged (Davis 1966). Stands ntaining trees of several ages that develop with significant interaction with sur- unding trees of different ages are classified as uneven-aged.

From this ecological-silvicultural basis, the forest manager must decide whether e individual stand is large enough to be recognized and managed as a separate treat- nt unit. A treatment unit composed of a single even-aged stand is usually managed der the even-aged system of management, and a unit composed of a pure all-aged stand managed under the uneven-aged system. Stands that are too small to be recognized separate treatment units are managed under the uneven-aged management system. Such treatment unit might be composed of several small even-aged stands or clumps--each o small to be treated separately. Thus, the choice between even- and uneven-aged nagement systems is dictated by silvicultural as well as economic and operational nsiderations. From a regulatory perspective, control variables of the two systems so differ. The major regulatory control variable in even-aged management is stand e (size) whereas the major control variables in uneven-aged management are stand ructure and stocking.

The remainder of this paper focuses on the major decisions facing forest managers o have adopted the uneven-aged system of management. We assume throughout this report at uneven-aged silviculture is a feasible alternative where its use is implied. stly, in the discussion that follows, the terms "treatment unit" and "stand" are used terchangeably. A stand is viewed as the smallest sized unit that can be efficiently naged.

# EARLY HISTORY OF THE PROBLEM

The philosophy of even-aged management, developed in Germany and Austria, is based the conviction that forest management is primarily a science for which mensurational ad financial formulas can be developed and used in a systematic manner. The concepts the fully regulated or normal forest and the doctrine of soil rent are outstanding amples of this form of thinking. Other examples include the myriad of methods for dtermining rotation length and allowable harvest levels--two of the major decision ints in even-aged timber regulation. Interfacing this philosophy with even-aged slvicultural practices is natural because even-aged silviculture is an easily under- ood system compatible with the concept that forest management can be systematized avis 1966; Knuchel 1953; Meyer and others 1961).

The philosophy of uneven-aged management was developed mainly in France and Switze land after the advancement of the even-aged philosophy. It was based on the concept that forest management is primarily an art that relies heavily upon the continuous input of the forester's ecological experience (with its scientific base) and silvicultura judgment in order to implement the management plan and to meet the stated objectives. This philosophy is compatible with the uneven-aged silvicultural system of selection harvesting where strong emphasis is also placed on the forester's experience and judgment (Davis 1966; Knuchel 1953; Meyer and others 1961).

A review of contemporary forest management literature reveals that uneven-aged management is still treated more as an art than a science (U.S. Department of Agriculture 1975, 1976). Additionally, the distinction between uneven-aged silviculture and management is often so blurred that many students of forest science have come to believe that uneven-aged management and silviculture are inseparable. In this paper, we show that the science of uneven-aged management is readily distinguishable from uneven-aged silviculture and that uneven-aged management is just as amenable to systematic treatment as is even-aged management.

Aside from obvious silvicultural and regulatory differences, the two management philosophies can be differentiated by what forest managers perceive to be the objectives of forest management, the relative weight assigned to each objective, and the methods used to achieve them. Knuchel (1953, p. 12), a Swiss forester who favored uneven-aged management, defined the objectives of forest management as follows:

1. Maintenance of the health and resistance to damage of the forest; raising the productive capacity of the soil and of the stands to the highest volume possible on the site and maintaining that productive capacity.

2. Continuous production of the highest possible volume of valuable timber.

3. Promoting the protective effect of the forest in the widest sense (protection against soil erosion, avalanches and flooding, protection of the scenery, protection of the native flora and fauna).

4. Provision of regular employment for the local inhabitants, especially during the time when labor is not wanted for agriculture.

5. Providing the highest possible financial yield.

6. The forest should work in a sense like a savings bank, in that in time of need it is in a position to supply a greater yield of material than in normal times, without losing its productive capacity.

While these objectives could also be met by even-aged management, many proponents of the uneven-aged philosophy believe that even-aged management fails to meet objectives 1, 2, 3, and 6. They believe that even-aged management results in the developme of a monoculture favoring a few species (primarily conifers) raised in single species age-homogeneous stands that are more susceptible to various damaging agents. They als contend that even-aged management has resulted in the conversion of "natural site" species to "introduced" species often with disastrous effects; the cutting of immature trees instead of producing the "...highest possible volume of valuable timber"; greate disturbance of the site with resultant impacts upon soil productivity, soil stability, scenic amenities, and native flora and fauna; and management plans that are disrupted when actual cutting deviates significantly from the scheduled cut.

The philosophy of uneven-aged management emphasizes protection and improvement of a stable forest environment, the guarantee of forest sustention and production of large-sized, high-quality timber. Its proponents believe that these objectives should not be sacrificed for higher rates of return on forest capital, greater wood fiber, an (or) management simplicity.

Forest management in the United States today generally follows the even-aged philosophy. Reasons are varied but can be attributed primarily to (a) the attractiveness of even-aged management as an effective means of converting a forest composed of decadent or high-graded stands to a regulated forest, (b) the dawning of the age of intensive management in the 1950's with its needs for more efficient means of managerial control, (c) the ease of implementing management prescriptions on the ground, and (d) the historic dearth of uneven-aged management techniques for large forest properties.

# THE PROBLEM TODAY

Recently, the Forest Service set aside a considerable amount of forest land acreage for "use influence," scenic, or backdrop zones to protect scenic amenities among others. A large portion of this land is at low elevations and has good access. The Forest Service action has taken the land out of normal timber production and has put it into a category designated for modified handling. Until recently, these special areas have received little or no treatment. With increasing demands for wood products, it is questionable if this condition will persist. These special areas seem ideal for the application of uneven-aged management principles.

In addition, the National Forest Management Act of 1976 restricts the Forest Service as to where and how even-aged management can be used. Thus, renewed attention has been focused on uneven-aged management as a system that may satisfy Congressional intent. Further, in 1975, the Forest Service evaluated the potential impact of various forms of uneven-aged silviculture during preparation of the Renewable Resources Program pursuant to the Resources Planning Act of 1974.

There is little doubt that these and other factors, such as public pressure, have stimulated renewed interest in uneven-aged management. Recently, the Forest Service conducted an eastern and western in-service workshop on uneven-aged silviculture and management (U.S. Department of Agriculture 1975, 1976; and Alexander and Edminster 1977a). Also, uneven-aged management is being conducted for selected tree species on both Indian and private industrial lands in the West (Steering Committee for Indian Reservation Forests 1977) and is used in the East, South, and Midwest (Davis 1966; Smith 1962; and U.S. Department of Agriculture 1973).

We feel that a forester should have a broad spectrum of management techniques, along with the necessary knowledge and tools to appropriately apply them, in order to best meet management objectives. Thus, it is important that both uneven-aged and even-aged management systems receive adequate attention and development. This is especially important in the case of uneven-aged management because the prevailing wisdom implies that this form of management is more of an art than a science--a time-honored doctrine that we challenge in this paper.

Given renewed interest in uneven-aged management, we believe that a summary of our current state of knowledge is in order. This summary is presented in three parts: (a) an examination of the major decisions facing managers who intend to practice uneven-aged management; (b) a discussion of the methods currently available to assist managers in reaching these decisions; and (c) a statement of future work required to improve and extend our knowledge of uneven-aged management systems.

# MANAGEMENT DECISIONS

Before an examination and evaluation of uneven-aged management tools can be made, the major decisions facing the forest manager interested in applying uneven-aged management must be specified and understood. Careful thought, coupled with a literature review of both European and American literature, suggests that most of these decisions can be reached when the following items have been thoroughly examined and decided upon:

1. *The optimal, sustainable diameter distribution for a given stand, expressed as number of trees in each diameter class.*--Under this definition, determination of optimal diameter distribution also establishes optimal stocking and maximum tree size because of their interrelationships. The form of the optimal diameter distribution, its stocking, and maximum tree size historically have been treated separately. This historical separation was probably the result of the methodology used at that time to derive the desired number of trees in each diameter class. There is nothing to indicate that these decisions must be treated separately. The true question facing the manager is, "How many trees should I maintain in each diameter class in order to meet the stated objectives?"

The criterion of optimality depends upon management objectives and constraints. For example, the objective might be to maximize fiber production, expressed as total stem cubic-foot volume, with the constraint that a minimum number of trees be maintaine in specific diameter classes for wildlife protection and esthetic amenities. Other optimization criteria could be to maximize saw log production, present net worth, cash flow, or marginal value growth percent. In addition to management objectives and constraints, it is expected that the optimal diameter distribution will vary depending upon forest species, cutting cycle length, and site quality.

2. *The optimal species mix for a stand.*--Besides its influence upon the form of optimal diameter distribution, species is also important in meeting management objectives. The objectives of maximizing fiber production might favor one species or species mix while another species may be best for maximizing saw log or veneer production, marginal value growth percent, or wildlife habitat requirements.

3. *The optimal cutting cycle length for each stand.*--Again management objectives play a significant role. However, constraints, such as minimizing disturbance to stand and site, physical and economic accessibility, and (or) logging equipment limitations also can influence the optimal cutting cycle length. Also, it should be remembered that cutting cycle length will influence optimal diameter distribution.

4. *The optimal conversion strategy and conversion period length for each stand.*--Given that the optimal diameter distribution for a desired species and cutting cycle length has been established, it is necessary next to determine the optimal cutting strategy for converting existing stands to the optimal sustainable condition. Intimate related to this is the question of optimal length of the conversion period for meeting management objectives.

5. *The optimal scheduling of compartment treatments and the date of entry for each compartment.*--Compartments, delineated by permanent boundaries, are typically defined as the primary unit of management, and are composed of one or more treatment units (hereafter labeled stands). Management decisions 1-4 have dealt with individual stands in each compartment. Ultimately, however, the manager is interested in learning how to schedule treatments in each stand so that his objectives for the forest as a whole will best be met. A possible constraint of management might be to treat all stands in a compartment at the same time. If so, previously determined optimal stand

reatments may have to be modified in order to meet forestwide objectives. When to irst enter each compartment for optimal results is also of concern. Other constraints ight be to maintain a minimum and (or) maximum wood flow in order to meet and (or) not xceed manufacturing capabilities; to maintain a nondeclining, even flow of wood; to enerate a desired cash flow; or to maintain a minimum or maximum staffing level. The olution to this final problem, which incorporates all preceding questions, will provide he "allowable" cut for each planning period that best meets the objectives of management.

## AN EARLY ATTEMPT TO ANSWER QUESTIONS

Matthews (1930) made an early attempt to quantify some of the aspects of uneven-ged management in this country in order to answer questions concerning conversion trategies, length of cutting cycle, "rotation" length (age of oldest tree in the tand), and allowable cut. Lacking better information, he assumed that the uneven-aged tand could be viewed as a composite of small, equal-sized, even-aged components that re well mixed throughout the stand. Therefore, his concept of the "ideal" structure f the uneven-aged stand could be determined by data taken from normal yield tables of ven-aged stands. This concept of the structure of uneven-aged stands was later laid o rest by Walker (1956) and Reynolds (1954), Walker concluding that to characterize neven-aged stands in such a manner was "..misleading, inaccurate, and a waste of ime."

## DE LIOCOURT'S CONSTANT "q" VALUE

In another attempt to quantify some of the aspects of uneven-aged management, yer (1943, 1952) and Meyer and others (1961) took the work of French forester Liocourt, expanded upon it, and applied it to forests in Mexico and the United ates. What de Liocourt found was that a balanced, or sustainable, diameter distri-tion was characterized by a constant "q" value, calculated as the ratio of the number trees in a given diameter class divided by the number of trees in the next larger ameter class, and by the diameter of the largest tree in the stand. This relationship nerates a geometric series and, when plotted, forms the well-known reverse-j shaped rve. Meyer demonstrated how knowledge of the balanced diameter distribution, coupled th additional information concerning present stand structure and growth, could be ed to develop a conversion strategy and to estimate future yields.

Duerr and Bond (1952) next examined how, after the best "q" value, species, and rgest tree size were determined, the economic criterion of marginal value growth rcent could be used to determine optimal stocking, in terms of volume per acre. timal stocking was defined as the stocking level at which marginal value growth rcent equals the alternative percent rate of return.

Hough (1954) used double sampling to collect growth and diameter distribution ta. He used these data to determine a targeted "q" value and a maximum tree size sed on the objectives of management and the form of the original diameter distribu-on. Then he compared the balanced diameter distribution to the predicted diameter stribution at the end of the first cutting cycle to determine the number of trees cut in each diameter class. For each area under control, this process was repeated st prior to scheduled harvesting. Hough theorized that this repetitive technique uld cause the targeted "q" value to approach, over time, the ideal "q" for the given ecies and site.

Leak (1964) extended de Liocourt's concepts to the unbalanced forest by modeling "q" as a function of diameter, instead of a constant. His objectives were to provide a means for classifying and (or) comparing different diameter distributions; "to aid in describing intermediate or short-term structural goals; and to provide a guide in marking operations."

In the latest development of the "q" concept, Moser (1976) describes a process for determining the distribution of a given amount of stand density (as measured by basal area, tree-area ratio, or crown competition factor) across a diameter distribution in which "q" and the maximum and minimum diameters have been specified.

The early attractiveness of de Liocourt's ideas was probably due to the following: the method provided a quantitative basis for determining an "ideal" or "normal" selection forest to use as an objective; it was useful in determining conversion strategies and allowable cuts; and the method was easy to use at a time when most calculations wer tediously done by hand. The recent literature would indicate that these features are still valued (Moser 1976; U.S. Dep. Agriculture 1975, 1976; and Alexander and Edminster 1977a, 1977b).

Some of the questions not answered by de Liocourt's methods were: (a) what "q" value and largest tree size combinations were optimal; (b) were the conversion strategies optimal or even desirable; (c) what about species composition, cutting cycle length, date of entry, and conversion period length; and (d) what compartment schedules were best for a given set of objectives?

More fundamentally, is a balanced distribution, such as that described by de Liocourt, necessary for sustention? Might not other diameter distributions be just as sustainable and yet prove to be better able to meet management objectives? These questions were probably on Davis' (1966) mind when he concluded that, "...a good diameter distribution is determined by the biology of the forest and the purposes of management and not by mathematics...." Leak and Filip (1977), in discussing the use of group selection in northern hardwoods, supported that conclusion.

# RECENT WORK

Some of the most important recent work dealing with the questions of uneven-aged management has been that of Adams (1974) and Adams and Ek (1974, 1975). Their work involves the interfacing of a stand simulator with nonlinear mathematical programing t answer questions concerning optimal stand diameter distribution, cutting cycle length, and conversion strategy. Their stand model was a modified version of a previously developed stand simulator (Ek 1974).

This simulator was used to determine the optimal stand structure that would maximize value growth for a fixed basal area stocking level, cutting cycle length, species mix, and site quality while meeting the constraints of sustainability. This process was repeated for various basal area stocking levels and the resulting different diamet distributions were compared by using the marginal value growth percent criterion to determine the final, optimal distribution for a fixed cutting cycle length, species mi and site quality. Adams (1976) subsequently has shown how this same procedure can be used to determine the optimal diameter distribution based on "value" stocking rather than basal area stocking. Distributions derived in this fashion are "investment-efficient" because they maximize percent net worth for the investment made in the grow stock.

One requirement of this procedure is that the cutting cycle be equal to, or an nteger multiple of, the growth period length of the model. In their example, Adams nd Ek (1974, 1975) used a cutting cycle equal to the growth period; however, they also howed how to incorporate longer, multiple period cutting cycles into their optimiza- ion process.

After establishing the optimal stand diameter distribution, Adams and Ek (1974, 975) used nonlinear mathematical programing to find the optimal conversion strategy hat maximized present net worth of the stand for a fixed conversion cycle length, pecies mix, and site quality during the transition from existing stand diameter distri- ution to optimal distribution. Like the cutting cycle length, the conversion cycle ength must be an integer multiple of the growth period. It is also possible to apply he same technique for different transition periods in order to determine the optimal onversion period length on a stand basis.

# WHAT'S NEXT

The milestone work of Adams and Ek (1974, 1975) opens the door to a new set of ools for answering uneven-aged management questions and illustrates that uneven-aged nagement is subject to much more rigorous analysis than many previously thought. evertheless, the development of uneven-aged management systems still lags behind that f even-aged management.

While Adams and Ek (1974, 1975) have incorporated conceptually most of the major ecision points facing a manager, their entire analysis was directed at single stands. onsequently, they did not consider the scheduling of compartment or stand treatments iewed from a forestwide position. Secondly, their approach did not adequately treat e problem of determining optimal species mix within a given stand. Lastly, some mputational problems remain when more complex situations are encountered. In review- g the work of Adams and Ek (1974, 1975), we believe that five problem areas, some erlapping, need additional work before their (or any other new) tools can be made lly operational. These problem areas are:

1. Improvement of computer and algorithm capabilities.

2. Development of techniques for interfacing stand simulators to nonlinear ograming models.

3. Development of uneven-aged growth and yield simulators.

4. Development of techniques for determining optimal species mixes.

5. Development of optimization tools for scheduling compartment treatments o a forestwide basis.

# COMPUTER AND ALGORITHM CAPABILITIES

In applying their techniques, Adams and Ek (1975) found that the solution process fast approached the limits of either the mathematical programing algorithms or the computer when the cutting cycle exceeded three times the growth period length. A similar problem existed when solving for the optimal conversion strategy. In this case, they discovered that transition periods exceeding four times the growth period could not be handled.

They found also that it was sometimes difficult, if not impossible, to find solutions to these nonlinear programing problems. But, as they suggest, there is reason t believe that some of these problems and limitations soon will be overcome either by applying new mathematical programing techniques, such as the optimal control theory or the decomposition theory, and (or) through improved computer capabilities.

# INTERFACING SIMULATORS TO NONLINEAR PROGRAMING

An important requirement of the Adams and Ek (1974, 1975) approach is a stand simulator that explicitly expresses the change in number of trees in a diameter class as function of the number of trees in the diameter class and as a function of any other applicable independent variables. Ek's (1974) modified stand simulator is the only uneven-aged simulator reported to date that meets this requirement. Although other modeling techniques do not provide the required explicit equations, it is possible to use numerical analysis procedures to provide estimates accurate enough to determine solutions without the explicit functions (Adams 1974). While theoretically possible, further research is needed to test the feasibility of this approach. One potential problem might be the difficulty in combining the nonlinear mathematical program, the program for the numerical analysis procedure, and the growth and yield simulator together on the same computer.

# GROWTH AND YIELD SIMULATORS

Given that the practical problems with interfacing nonlinear programing to a growth and yield simulator can be worked out, one is then faced with a wide choice of simulator types to choose from. Munro (1974) classified simulators into three categories: single tree/distance dependent, single tree/distance independent, and whole stand/distance independent.

Single tree/distance dependent simulators utilize tree coordinates to appraise intertree competition between a given tree and its neighbors. An example of a simulator of this type with the potential for use in uneven-aged stands is the one reported by Ek and Monserud (1974a, 1974b). The theoretical advantage of this type of simulator is that it can provide the greatest amount of information concerning both tree and stand development. However, the single tree/distance dependent simulators published to date have not demonstrated an ability to predict individual tree development accurately, and they do not seem to predict stand attributes any better than the other types of simulators. It is possible that these results will improve as the "state of the art" improves.

There are several disadvantages to using single tree/distance dependent simulators for answering uneven-aged management questions. First, this type of simulator is difficult and expensive to develop because data with individual tree coordinates are not common. The simulators are also more costly to operate because of the tree coordinate data needed to initialize them and because of the large amount of computer time and space needed to run them.

Second, much of the data generated by this type of simulator are not needed to answer uneven-aged management questions. Thus, there is also a real potential for overloading the information system with extraneous data.

Third, the small plots usually generated by single tree/distance dependent simulators may not be large enough to represent the uneven-aged stand accurately. Finally, because of the large amount of computer space and time needed, it is doubtful that a simulator of this type can be interfaced with nonlinear programing.

Some modelers, who have developed single tree/distance dependent simulators, have tried to circumvent the expense and difficulty of requiring tree coordinates when the simulator is initialized by artificially generating tree coordinates. This basically converts the simulator to a distance independent type insofar as later usage is concerned (Munro 1974).

An example of a single tree/distance independent stand simulator that has the potential for adaptation to uneven-aged stands is Stage's (1973) "prognosis model." Stage's approach has several advantages over the distance dependent type. Besides the obvious advantages of not requiring tree coordinates, his approach does not require the complete enumeration of the plots to be "prognosticated." Instead, it is based on samples drawn from throughout the stand. This lessens the amount of data to run the model and makes it possible to apply the model to uneven-aged stands, which are often large in size.

The disadvantages of single tree/distance independent simulators are that their programs are still large and generate a large amount of information not presently needed to answer uneven-aged management questions. Because of their size, the interfacing of the distance independent simulators with nonlinear programing is as doubtful as with the distance dependent type. It is also generally acknowledged that single tree/distance independent simulators are not designed to provide accurate individual tree development information. Also, their advantage over whole stand/distance independent simulators for predicting stand development has not been demonstrated.

Whole stand/distance independent simulators can range from the simple to the complex. Moser's (1972) set of first-order, ordinary differential equations for expressing change in the total number of trees (or in total basal area) of the stand is an example of a simple uneven-aged whole stand simulator. The differential equations were used to express gross growth, mortality, and ingrowth rates for all trees 7 inches or greater in size. In a later version, Moser (1974) divided the stand into six diameter classes (1.6-4.5, 4.6-9.5, 9.6-14.5, 14.6-19.5, 19.6-24.5, and 24.6+inches). This improvement allowed the monitoring of changes in diameter distribution because of different treatments. For each diameter class, differential equations were again used to model gross growth, mortality, and ingrowth, this time expressed as basal area, cubic-foot volume, or number of trees.

Ek's (1974) uneven-aged stand simulator is also fairly simple. He divided the stand into 2-inch diameter classes and then used a technique analogous to stand table projection to move the trees through the diameter classes. The changes in the number of trees in each diameter class due to ingrowth, upgrowth, and mortality were modeled as nonlinear functions.

The whole stand/distance independent type of simulator is easier to develop, cheaper to initialize and run, and takes less computer core than do the single tree varieties. Also, its smaller computer core requirements make it more likely to be interfaced with nonlinear programing. The main disadvantage is that individual tree information is completely lacking and, for the very simple whole stand simulators, stand structure information is sometimes lacking. However, as was mentioned, the lack of individual tree information is not critical at this time for two reasons: (a) the information is not needed to answer most of the uneven-aged management questions, and (b) simulators that produce individual tree information have not demonstrated an ability to do so reliably.

We believe that relatively small uneven-aged, whole stand/distance independent simulators can be developed that will provide more detailed information than do present whole stand simulators about stand structure and about the growth and vigor of tree classes within the stand. The progress of our work tends to confirm this hypothesis. Once our simulator is completed, we hope that a numerical analysis linkage to a nonlinear programing routine can be developed and tested for feasibility.

## SPECIES COMPOSITION

Both Moser's (1972, 1974) and Ek's (1974) whole stand/distance independent simulators were developed from mixed species data. None of the simulators recognized individual species; so the estimated yields represent only the species mix found in their data. Determining an optimum species mix is an important question for forest managers interested in practicing either even- or uneven-aged forest management. Adams and Ek (1975) concluded that the best way to approach the species composition problem was to use a single tree/distance dependent simulator and a growth maximization algorithm. They rejected using whole stand/distance independent simulators because they believed that (a) multispecies whole stand simulators would be almost as complex as single tree types and (b) determining the parameters in the nonlinear, multispecies equations would tax or exceed existing nonlinear regression programs.

We do not agree. Multispecies whole stand simulators undoubtedly will be more complex than single tree simulators, but we do not feel that they will approach the complexity of individual tree/distance dependent simulators. The problem of nonlinear regression limitations can also be avoided through the use of other modeling strategies.

We base these conclusions on our work in developing a whole stand/distance independent simulator for uneven-aged ponderosa pine. In this simulator, ponderosa pine has been divided into two vigor classes, "blackjack pine" and "yellow pine," based on bark color of the tree. Each vigor class is represented by a separate diameter class distribution. As a result, each vigor class has been handled in a manner analogous to the treatment of separate species in a multispecies model. Separate growth and mortal functions have been developed that interrelate both vigor components of the stand. We have not encountered insurmountable problems modeling these two vigor classes, and we do not believe the simulator is overly complex. A similar approach is worth trying for multispecies simulators.

Given that a simulator can be developed for multiple species, the optimization problems are merely logical extensions of Adams' and Ek's work. As an example, the following formulation is used to determine the optimal diameter distribution for two species ($X$ and $Y$) and a specified level of stocking ($L$):

$$\max_{[X_D(t),\ Y_D(t)]} \sum_{D=1}^{N+1} V_D \cdot \Delta X_D + \sum_{D=1}^{M+1} U_D \cdot \Delta Y_D$$

subject to:

$$\Delta X_D \geq 0, \quad D = 1, \ldots, N + 1$$

$$\Delta Y_D \geq 0, \quad D = 1, \ldots, M + 1$$

$$\sum_D (f(D) \cdot (X_D(t) + Y_D(t))) = L$$

$$X_D(t) \geq 0, \quad D = 1, \ldots, N$$

$$Y_D(t) \geq 0, \quad D = 1, \ldots, M$$

In this formulation, $V_D$ and $U_D$ are value functions of diameter for species $X$ and $Y$, respectively; $\Delta X_D$ and $\Delta Y_D$ are the changes in the number of trees in the $D$th diameter class after one growth period; $f(D)$ is the function that determines diameter class stocking; and $X_D(t)$ and $Y_D(t)$ are the initial number of trees in the $D$th diameter class. By eliminating all terms involving species $Y$, the exact one-species formulation of Adams and Ek (1974) results.

An unexplored area is the feasibility of linking a multispecies model with a nonlinear programing routine. Although theoretically possible, such a model might encounter computational limitations. Additional research is needed before definite conclusions can be drawn.

# SCHEDULING OF COMPARTMENTS

The preceding discussion of management decisions 1 through 4 shows that foresters only recently have begun to apply modern decisionmaking tools to help solve uneven-aged management problems. Further, a review of the literature indicates that most of this recent work is directed at the individual treatment unit or stand and not at the forest in its entirety. In fact, little attention has been paid in the literature to the scheduling of uneven-aged compartments for treatments. Loucks (1964) observed that linear programing could be used to schedule treatments in uneven-aged forests, and Norman and Curlin (1968) applied linear programing to the management of a Tennessee Valley Authority (TVA) forest organized for uneven-aged management. The Forest Service Timber Resource Allocation Model (Timber RAM) also is capable of handling uneven-aged management options (Navon 1975). Further, we understand that the mathematical programing system, Max-Million (Ware and Clutter 1971), used extensively to schedule harvest operations in the Southern States has been modified by some users to include uneven-aged management options. Thus, it is apparent that linear programing can be used to facilitate scheduling when an uneven-aged management system is used. To clarify this, we will examine the scheduling problem in more detail, pointing out difficulties to be overcome. A simplified linear programing formulation and two alternative formulations are then proposed. Each formulation is to illustrate one way to interface stand-level information, such as might come from the work of Adams and Ek (1974, 1975), with a forestwide optimization model.

Although optimal stand structure, species composition, and conversion strategy may be determined for each stand, it is highly unlikely that these optimal stand solutions will lead directly to an optimal forestwide scheduling solution. Preliminary work indicates that the decision points for each stand that can be determined by scheduling are time of first entry, cutting cycle length, and conversion length. Therefore, the alternative treatment schedules for each uneven-aged stand are a series of yields that are the result of determining optimal stand structure, species composition, and conversion strategy for a selected set of alternative cutting cycles, conversion lengths, and times of first entry.

We assume at the outset that the forest area has been organized into geographically identifiable compartments, with each compartment composed of one or more individual treatment units or stands. We further assume that all stands are to be treated and managed as uneven-aged stands. However, this assumption can be relaxed without major impact on the formulation that follows. The planning horizon (that is, the number of years over which we wish to plan) is split into a series of planning periods, each of constant length, and an equal multiple of the growth period. This latter assumption is necessary if Adams' and Ek's (1974, 1975) stand optimization procedures are to be used to produce stand-level inputs. However, this limitation may be eliminated if a different approach to stand simulation is adopted. As previously noted, the cutting cycle and conversion length are also restricted to even multiples of the growth period.

We also assume that the scheduling of management activities is done at the compartment level and not at the stand level. Later, we alter this assumption by eliminating compartment boundaries and, in essence, treat the whole forest as a single compartment made up of many stands. For treatment activities, it is necessary to recognize individual stands within compartments. We deal with this by aggregating stand information within a compartment, but we preserve the integrity of the compartment for scheduling purposes.

For each stand in a given compartment, a set of management alternatives is gener-ted. As shown in table 1, each management alternative is characterized by its cutting ycle, conversion length, and date of first entry. One of the management alternatives s assumed to represent the optimal cutting cycle, conversion period, and conversion trategy for a given stand provided by a procedure similar to that of Adams and Ek 1974, 1975). However, this condition can be eliminated without affecting the formula-ion of the scheduling problem. The remaining management alternatives for each stand re clearly not optimal, but are included to facilitate the compartment level optimiza-ion. Compartment summaries are obtained by totaling all stand variables (weighted by tand size) over a given planning period.

Table 1.--*Example of management alternative specification format*

| Management alternatives | | 5-year planning period | | | | | Net present value |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | ... | |
| Compartment i | | | | | | | Stand 1 |
| 1 | [1]CC = 10<br>[2]DE = 1 | [3]V | | V | | | C |
| 2 | CC = 10<br>DE = 2 | | V | | V | | C |
| 3 | CC = 5<br>DE = 1 | V | V | V | V | | C |
| .<br>.<br>. | | | | | | | |
| n | CC = 5<br>DE = 3 | | | V | V | | C |
| | | | | | | | Stand 2 |
| 1 | CC = 10<br>DE = 1 | V | | V | | | C |
| 2 | CC = 10<br>DE = 2 | | V | | V | | C |
| 3 | CC = 5<br>DE = 1 | V | V | V | V | | C |
| .<br>.<br>. | | | | | | | |
| n | CC = 5<br>DE = 3 | | | V | V | | C |
| | Summary for compartment i | | | | | | |
| 1 | | V | | V | | | C |
| 2 | | | V | | V | | C |
| 3 | | V | V | V | V | | C |
| .<br>.<br>. | | | | | | | |
| n | | | | V | V | | C |

[1]CC = Cutting cycle.
[2]DE = Date of entry.
[3]V = Volume removed at time of harvest.

While the date of first entry is a useful descriptive variable, it is not used as a control variable in the compartment level optimization. However, it must be equal t or evenly divisible by the cutting cycle and conversion period in our formulation.

The manner in which management alternatives are defined for each stand within a compartment can greatly affect the computational feasibility of the approach being developed. For instance, if a common definition of management alternatives is forced upon each stand in a compartment (as in table 1), the total number of alternatives to examine will be equal to $\sum_{i=1}^{c} a$ where $a$ = the number of alternatives per stand and $c$ = the compartments.

However, if each stand in a given compartment adopts a unique definition for its management alternatives, then the total number of alternatives mushrooms to $\sum_{i=1}^{c} a^{s_i}$ and $s_i$ = number of stands in the $i$th compartment.

A compromise solution to this problem is possible if a priority ranking of management alternatives of each stand within a compartment is determined. This would undoubtedly lead to suboptimization, but would be better computationally than the first approach and more feasible than the second.

Based upon one of the above options, we can proceed to formulate the compartment level scheduling problem as a linear program. Although we assume that our objective is to maximize net present value over the planning horizon, other objectives are equally possible. In so doing, we also assume that the demand for stumpage is perfectl elastic between $U_k$ and $L_k$ (see below). We define

$X_{ij}$ = the number of acres in compartment $i$ to manage under management alternative $j$

$V_{ij}$ = the harvest volume per acre removed from compartment $i$ if managed under management alternative $j$

$i$ = the compartment index where $i = 1, 2, \dots m$

$j$ = the management alternatives index where $j = 1, 2, \dots n$

$k$ = the planning period index where $k = 1, 2, \dots t$

$C_{ij}$ = net present value ($NPV$) per acre if compartment $i$ is managed according to management alternative $j$

$U_k$ = the upper bound on the desired harvest volume in planning period $k$

$L_k$ = the lower bound on the desired harvest volume in planning period $k$

$A_i$ = the maximum acreage in compartment $i$ available for management

We then have

$$\text{Max } NPV = \sum_{i} \sum_{j} C_{ij} \cdot X_{ij}$$

subject to

$$\sum_i \sum_j V_{ij} \cdot X_{ij} \leq U_k \qquad \text{for all } k = 1, 2, \ldots t$$

$$\sum_i \sum_j V_{ij} \cdot X_{ij} \geq L_k \qquad \text{for all } k = 1, 2, \ldots t$$

$$\sum_j X_{ij} \leq A_i \qquad \text{for all } i = 1, 2, \ldots m$$

Under this formulation, $X_{ij}$ is treated as a continuous decision variable implying that a compartment can be managed under more than one alternative. This further implies a management strategy for a compartment that involves different cutting cycles and different dates of first entry. However, as long as all of the above cycles or periods are equal multiples of each other, the management strategy presents no serious scheduling problem. The real problem lies in the fact that if a stand is managed under two or more management alternatives, no guidance is given for locating the portion of the stand to be managed under each alternative.

As an alternative to the above formulation, we may wish to treat the whole compartment using one management alternative. To accomplish this, we redefine some of our variables. In this case, let

$X_{ij}$ = the proportion of compartment $i$ managed under management alternative $j$

$C_{ij}$ = the total net present value from compartment $i$ if managed under management alternative $j$

$V_{ij}$ = the total harvest volume from compartment $i$ if managed under management alternative $j$

We also require that $X_{ij}$ takes on the value of 0 or 1.

Generally, the above integer programing problem will be more difficult to solve computationally than the linear programing formulation previously presented. Thus, if an integer solution is desired, a common definition of management alternatives probably would be required to reduce the computational load.

The linear and integer programing problems presented above have been based on the premise that the compartment is the basic unit of management and the stand the operational unit for which a specific silvicultural treatment is specified. Thus, both formulations restrict entry into stands in a given compartment. Since the cutting cycles for all stands in a given compartment are equal multiples of each other, one or more stands are treated during each planning period.

As an alternative, we may do away with compartment boundaries entirely and schedule individual stands. In this case, the maximum number of management alternatives to consider is $\sum_{i=1}^{c} a \cdot s_i$, where $a$, $c$, and $s_i$ are as previously defined.

Under this approach, a stand could still be managed under two or more management alternatives. This can be avoided if an integer programing formulation is adopted. However, as mentioned earlier, the computational difficulty associated with solving this type of problem mounts rapidly as management alternatives increase in number.

Techniques for scheduling treatments for uneven-aged stands do not differ markedly from those used for even-aged management. Further, it makes no difference if even-aged stands are intermingled with uneven-aged stands. Thus, we believe that with few exceptions, uneven-aged management systems can be developed for large forest properties. However, actual case studies of this approach are not available in the literature.

# SUMMARY

The use of uneven-aged forest management has been limited in this country. One reason for this might be the belief that the practice of uneven-aged management is more of an art than a science. As a result, historically, few tools have been developed to aid the manager interested in applying uneven-aged management. However, recent Congressional and administrative decisions, along with increased public concern and involvement in forest management decisionmaking, are forcing uneven-aged management to be reevaluated as an alternative to current practices. With increased interest has come initial development of tools that can help the manager answer some pressing questions about uneven-aged management. Some aspects of uneven-aged management may remain an art but evidence is growing that more science can be introduced into it than previously was thought.

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KEYWORDS: uneven-aged, even-aged, forest management, silviculture, management decisions, stand simulation, mathematical programing, optimization, compartment scheduling.

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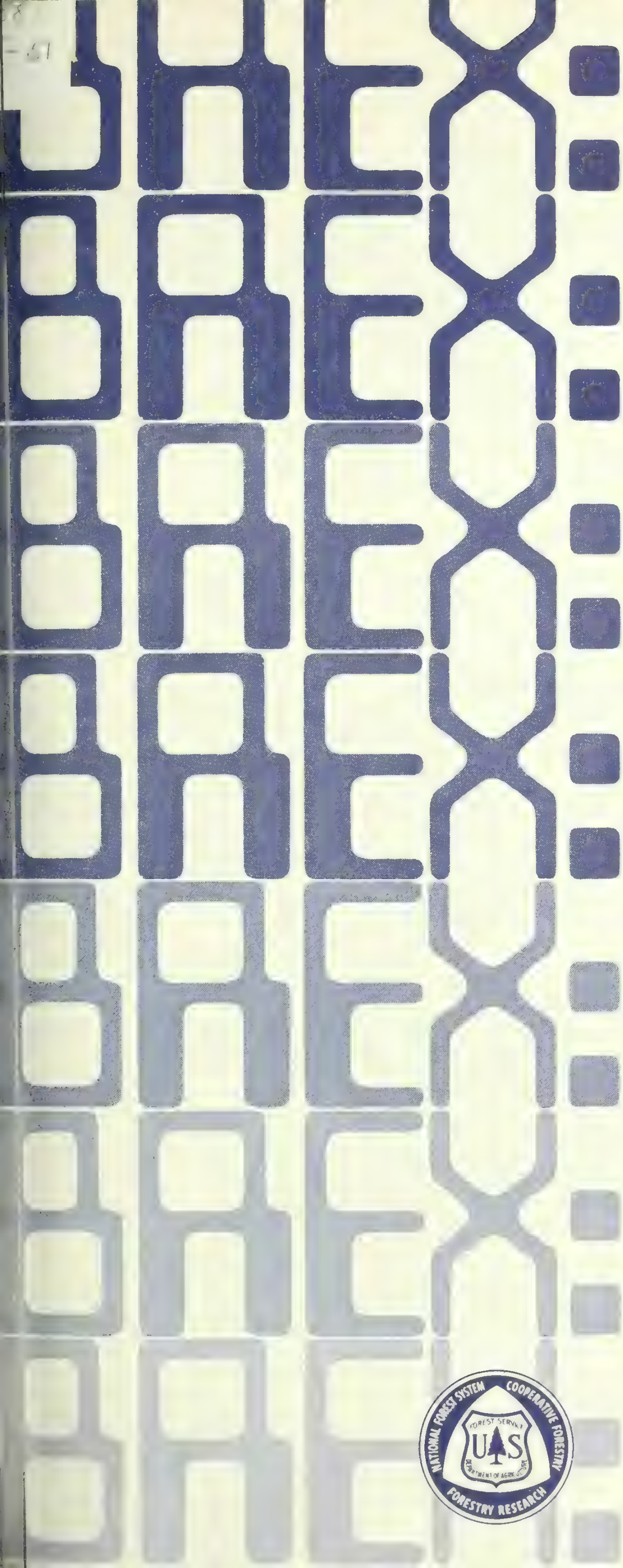

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# A computer program for applying ridge regression techniques to multiple linear regression

**Brian R. Mitchell**
**and**
**David W. Hann**

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RANGE EXPERIMENT STATION
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# BREX: A COMPUTER PROGRAM FOR APPLYING RIDGE REGRESSION TECHNIQUES TO MULTIPLE LINEAR REGRESSION

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# RESEARCH SUMMARY

An algorithm for ridge regression (BREX) is presented which can be used in conjunction with Grosenbaugh's REX (1967), a linear regression program with combinatorial screening. The algorithm uses either REX punched matrix input, or raw data with suitable transformations, to estimate ridged (biased) regression coefficients. A modification of Marquardt's (1970) criterion is proposed for selecting the best biasing level (k value). Application of the algorithm is demonstrated on two widely-used data sets (Hoerl and Kennard, 1970b; Draper and Smith, 1966).

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# INTRODUCTION

Multiple linear regression is one of the most commonly used statistical techniques in forestry. Regression analysis is used routinely to develop growth and yield models and to estimate individual tree and stand volumes. This process can be divided into three components: model hypothesis, screening of variables in the hypothesis, and parameter estimation for the final model.

While many criteria have been proposed for selecting the best subset of variables, screening all combinations does guarantee that the best set is actually found (Hocking 1976). Grosenbaugh (1967) developed a program, REX, that selects the independent variables by screening all combinations and picking that combination which minimizes the relative mean-squared error (relative mean-squared error is defined as the ratio of the regression mean-squared error to the variance of the dependent variable). REX then uses the least-squares criterion to estimate the regression parameters. These estimates are the best linear unbiased estimates (BLUE's) for the model, but in the presence of multicollinearity they may be too imprecise to be useful. Multicollinearity exists when at least one independent variable is highly correlated with another, or with a linear combination of other independent variables. The high degree of imprecision is due to the fact that multicollinearity between independent variables causes the correlation matrix to approach singularity and the variances of the parameter estimates to approach infinity.

When faced with multicollinearity, the analyst may be tempted to eliminate those independent variables causing the problem by consciously removing them from the model or by using a screening method, such as stepwise regression, which has a tendency to exclude such variables. However, this may destroy the usefulness of the model by eliminating relevant independent variables.

Another approach for dealing with multicollinearity is to apply ridge regression methodology. A ridged solution produces biased estimates of the model parameters, but it can also greatly reduce the variances of the parameters so that the sum of their mean-squared errors (MSE) is less than that for the least-squares solution. By combining ridge regression with a least-squares program that screens all combinations, it is possible to first select the set of variables which minimizes MSE, and then minimize any resulting multicollinearity problems by ridging the parameter estimates.

For those interested in using a model for predictive purposes, the ridged model offers two advantages over the least-squares model. First, the ridged model has a lower MSE value than the least-squares model; this increases confidence in predictions (Hoerl and Kennard 1970a). Second, the ridged coefficients can often meet theoretical or practical constraints on the model when the least-squares estimates are of wrong sign or magnitude (Hoerl and Kennard 1970b). The latter feature is particularly important if the model is to be used outside of the range of the original data set, as is often the case in simulation.

For users primarily interested in interpreting the regression coefficients, the presence of multicollinearity causes serious problems. Kmenta (1971) has shown that the least-squares estimates are highly imprecise under high multicollinearity. By using ridge regression, the precision of the regression coefficients is increased and interpretation becomes more dependable.

This report presents a computer program, BREX (biased REX), which computes ridge estimates from the moment matrix output of REX. For those who do not use REX, BREX can also be run using raw input data.

# PRINCIPLES OF RIDGE REGRESSION

## Ridge Regression

The multiple linear regression model is commonly written as,

$$Y = XB + e \tag{1}$$

where $Y$ is the $n$ vector of observations on the dependent variable, $X$ is the $nxp$ matrix of observations on the independent variables, $B$ is the $p$ vector of parameters, and $e$ i the $n$ vector of errors. It is assumed that $X$ has full rank $p$ and

$$E(e) = 0 \qquad E(ee') = \sigma^2 I \tag{2}$$

For convenience, it is also assumed that all the variables have been standardized so that the sample means are zero and the sums of squares are one. The moment matrix, $X'X$, then consists of the sample correlation coefficients (Draper and Smith 1966).

The least-squares estimates are given by

$$\hat{B} = (X'X)^{-1}X'Y \tag{3}$$

with variance-covariance matrix,

$$COV(\hat{B}_i, \hat{B}_j) = \sigma^2 (X'X)^{-1} \tag{4}$$

The diagonal elements of the inverse of the correlation matrix are labeled the varianc inflation factors (VIF) by Marquardt and Snee (1975) since the variances of the estimated parameters are directly proportional to these factors. If the independent variables are uncorrelated, then

$$(X'X) = I = (X'X)^{-1} \tag{5}$$

and the VIF's are all equal to one. In the presence of high correlations, however, some of the VIF's become much larger than one and the corresponding estimates are very imprecise (Marquardt 1970). Because the least-squares estimates are the BLUE's for th model, the precision can only be improved by using nonlinear or biased estimators. Nonlinear estimation tends to be computationally difficult. Among the alternatives t nonlinear estimation are ridge regression, principal components, and shrinkage estimators. Ridge regression is the most popular biased method, probably because its relationship to least-squares and its statistical properties are clearly defined.

Hoerl (1962) first suggested that adding a small positive constant $k$ to the diagonal elements of $X'X$ would reduce the variances of the coefficients. The ridge estimates are

$$\hat{B}^* = (X'X + kI)^{-1}X'Y,\ k>0 \tag{6}$$

with variance-covariance matrix,

$$COV(\hat{B}_i^*, \hat{B}_j^*) = \sigma^2(X'X + kI)^{-1}X'X(X'X + kI)^{-1}. \tag{7}$$

Note that for $k = 0$ the ridge estimates are equal to the least-squares solution.

Hoerl and Kennard (1970a) have shown that although the ridge estimates are biased, there always exists a $k>0$ such that the sum of MSE's of the parameter estimates is lower than for least-squares. Hocking and others (1976) have concluded, however, that ridge regression is not necessarily superior to least-squares when the number of independent variables is less than three. Vinod (1976) and Marquardt and Snee (1975) have argued that minimal MSE is a better criterion than BLUE for judging the quality of regression estimators. An estimator that is close to the true value with high probability, though biased, is thought better than an unbiased estimator which has a low probability of being near the true value.

## Selecting a "k" Value

Although ridging can always reduce MSE for nonorthogonal regressors, no closed-form solution exists for the $k$ value that minimizes the summed MSE. Hoerl and Kennard (1970b) proposed examining the ridged parameter estimates, $\hat{B}^*$, over a range of $k$ values (the ridge trace) and selecting one where $\hat{B}^*$ stabilizes. Since we are interested mainly in the variances of these estimates, this approach is indirect as well as very subjective. Stability is a matter of degree since, as $k$ goes to infinity, $\hat{B}^*$ approaches zero.

The situation is simplified if we transform the variables to their principal components (linear combinations of the variables which are mutually orthogonal) to obtain a generalization of ridge regression. Following Hilt and Seequist (1977), there always exists an orthogonal transformation matrix $P$ such that,

$$P'X'XP = D \text{ and } P'P = I. \tag{8}$$

The columns of $P$ are the eigenvectors of $X'X$, and $D$ is the diagonal matrix of corresponding eigenvalues. The least-squares regression coefficients on the principal components are given by

$$\hat{A} = D^{-1}\ P'X'Y \tag{9}$$

and the generalized ridge solution by

$$\hat{A}^* = (D + K)^{-1}P'X'Y \tag{10}$$

where K is a diagonal matrix with nonnegative elements $k_i$. The MSE of each element $a_i$ of $\hat{A}^*$ is minimized by setting $k_i = \sigma^2/a_i^2$ (Hoerl and Kennard 1970a). These optimal $k_i$'s depend on the unknown parameters $\sigma^2$ and $a_i$ which can be replaced with the consistent estimates, $\hat{\sigma}^2$ and $(\hat{a}_i)^2$. However, this substitution destroys the minimum MSE property (Vinod 1976). Since these least-squares estimates are generally poor due to ill conditioning, Hoerl and Kennard (1976) suggest that they only be used as a startin point to estimate initial values of the $k_i$'s. These $k_i$'s are then used to find a new and the iteration continues until convergence of the $k_i$'s to stationary values occurs. Hemmerle (1975) presents a closed-form solution to this iterative process, but finds that it often leads to an unacceptable increase in the error sum of squares (ESS). He proposes allocating the allowable inflation of ESS proportionally to each principal component. This method brings those $a_i$'s previously set to zero back into the solution, though they obviously contribute the most to variance inflation (Hocking and othe 1976). Until a more satisfactory procedure for constraining the increase in ESS is fo generalized ridge regression lacks practicality.

With ordinary ridge regression ($k_i$ = constant), one could average the generalized $k_i$'s to find a single $k$ value, the harmonic mean being suggested (Hoerl and others 197 to minimize the effects of small $a_i$'s which have little predictive value. This approa leads to the estimator,

$$\hat{k} = p\hat{\sigma}^2/\hat{A}'\hat{A} = p\hat{\sigma}^2/\hat{B}'\hat{B} \qquad (11)$$

where $p$ is the number of independent variables (the denominator is the length of the parameter vector which is unchanged by the switch to principal components). The same estimator arises by minimizing the summed MSE of the parameter estimates for the speci case where $X'X = I$. Again, the least-squares estimates are used as a starting point and then the iteration is continued on $(\hat{B}^*)'\hat{B}^*$ until the $k$ value converges.

This procedure was included as an option in an earlier version of BREX. We found that the initial least-squares estimates often produced $k$ greater than one and convergence to infinity occurred. Mallows' (1973) estimator,

$$\hat{k} = p\hat{\sigma}^2/(\hat{B}'\hat{B} - p\hat{\sigma}^2) \qquad (12)$$

was also considered since it is unbiased, but, as it is always larger than that of Hoerl and others (1975), the same problem would occur.

The most promising method for selecting a $k$ value was that of Marquardt (1970). He sought a $k$ value such that the maximum VIF was between 10 and 1, and closer to 1. Obviously, VIF's less than 1 are undesirable because 1 is the lower limit attained by a perfectly orthogonal system. BREX calculates both minimum and maximum VIF's, the former being a secondary criterion which preferably would be not much less than 1. Defining a desirable range such as this allows consideration of the increase in the ESS as well.

A further advantage of Marquardt's criterion is that $k$ is nonstochastic, dependin only on fixed $X$ (Obenchain 1975). This property is required if the equations derived by Hoerl and Kennard (1970a) for $E(\hat{B}^*)$ and $COV(\hat{B}_i^*, \hat{B}_j^*)$ are to be valid. The estimator previously discussed are stochastic, depending on $Y$, and therefore, technically, their moments are unknown.

# PROGRAM OPERATION

## Program Availability

BREX is written in FORTRAN IV and is operational on a CDC 6400 and a CDC CYBER 73. A copy of the program can be obtained by writing:

PROGRAM BREX
Renewable Resources Evaluation Research Work Unit
507 - 25th Street
Ogden, Utah 84401

## Features of BREX

BREX was specifically designed to be used in conjunction with Grosenbaugh's REX. For this reason, it uses as input the moment matrix punched by REX. To allow access by other users, subroutines MTRX and TRNX were added for the conversion of raw data to REX matrix form.

Control card input is assumed to be from cards, but the data matrix or observations may be read from tape. If raw data are used, punched output identical to that of REX can be requested for later reuse. For a large number of observations, efficiency is greatly increased by direct use of the moment matrix.

For each problem to be solved, the user can select ridge output for up to 10 specified $k$ values or accept the default selection of 20 values over the range 0.005 to 1.0. Like REX, the user can specify the use of the moment matrix from the previous problem for any problem except the first of a run. In this way, many possible models can be checked on a single run while only reading in the data once.

The first page of the output gives the problem title and a statement of parameters. For raw data, the first two and the last transformed observation vectors are displayed as a check against errors in TRNX or an incorrect number of observations.

The second page presents the least-squares solution with the standardized coefficients, and the normal coefficients and their variances. Also displayed is the estimated MSE, ESS, minimum and maximum VIF's and $\overline{R}^2$. Succeeding pages show the ridge solution for each $k$ value, giving statistics similar to those for the least-squares solution.

# Control Cards for the Use of BREX

| Field Function | Column | Name | Format |
|---|---|---|---|
| Card 1 | | | |
| Problem identification | 5-76 | NAME | 18A4 |
| Label for punched output (from raw data only) | 77-80 | NAME | A4 |
| Card 2 | | | |
| Total number of variables in REX input matrix or number of variables after transformation of raw data | 1-5 | NNT | I5 |
| Number of independent variables for this problem | 6-10 | NGX | I5 |
| Number of *k* values to be read in (0 = default selection) | 11-15 | NNK | I5 |
| Use data from previous problem? (Yes = 1, No = 0) | 16-20 | IPD | I5 |
| Should regression be performed without intercept?[1] (Yes = 1, No = 0) | 21-25 | IMO | I5 |
| Are input data from tape?[2] (Yes = tape number, No = 0) | 26-30 | ICT | I5 |
| Are the observations to be weighted?[1] (Yes = 1, No = 0) | 31-35 | IW | I5 |
| Number of observations for raw data input (= 0 for REX matrix input) | 36-45 | NOB | I10 |
| Number of variables (excluding weight) for each raw observation vector (= 0 for REX matrix input) | 46-50 | NVAR | I5 |
| Tape number for punched output[2] (= 0 for REX matrix input) | 51-55 | IPO | I5 |

(con.)

---

[1] Unlike REX, these options have no effect on REX matrix input except to provide correct labeling on the first page of output. Also, they cannot be used to change these specifications for a problem using data from a previous one. It is important to repeat the same specifications for previous data problems so that the output will be correctly labeled.

[2] The first statement of the main program specifies tape 7 for the punch and tape 10 for data input. If other unit numbers must be used, simply change the numbers in this statement.

# Control Cards for the Use of BREX (Cont.)

| Field Function | Column | Name | Format |
|---|---|---|---|
| Card 3 | | | |
| Punch $X$'s and a $Y$ in the columns whose ordinals are the subscripts of the independent variables and the dependent variable, respectively | 1-50 | NX | 50A1 |
| Card 4 | | | |
| Up to 10 $k$ values to be used, in order of ascending magnitude (blank for default selection) | 1-80 | XK | 10F8.4 |
| Cards 5 and 6 | | | |
| Variable format for raw data input (blank for REX matrix input) | 1-80<br>/1-80 | FMT | 20A4<br>/20A4 |

These six cards are followed by the input data if they are from cards. This sequence of cards (1-6 plus data cards, if any) is repeated for each problem in the run. After the last problem set, a card punched "DONE" in columns 1-4 signals the end of the run.

# Subroutine TRNX

This is a user-supplied subroutine that generates regression variables from raw data using FORTRAN statements. The input variables, *D(I)*, *I* = 1, NVAR, are read according to the variable format on control cards 5 and 6 of the problem set. The output variables, *X(I)*, *I* = 1, NNT, and the weight *W*, then are used to form the *X'X* matrix. TRNX is called once for each observation to assign values for all the independent and dependent variables to be used for all the problems of a run. For each problem set, control card 3 specifies the dependent variable and regressor variables in the particular model.

The cards labeled TRNX 10 through TRNX 110 are always required. In the example below, the raw variables are used untransformed with a constant weight of one.

```
          SUBROUTINE TRNX                                            TRNX  10
C                                                                    TRNX  20
C SUBROUTINE TRNX ALLOWS NVAR RAW INPUT VARIABLES D(I) TO BE         TRNX  30
C TRANSFORMED INTO (NGX+1) REGRESSION VARIABLES USING FORTRAN.       TRNX  40
C IF WEIGHTED REGRESSION, W MUST BE ASSIGNED A VALUE                 TRNX  50
C                                                                    TRNX  60
      COMMON/RMT/X                                                   TRNX  70
      COMMON/MT/D,W                                                  TRNX  80
      DIMENSION  D(50), X(50)                                        TRNX  90
      DO 1  I = 1, NVAR
      X(I) = D(I)
    1 CONTINUE
      W = 1.0
      RETURN                                                         TRNX 100
      END                                                            TRNX 110
```

# APPLICATIONS OF BREX

To demonstrate the use of BREX, we chose two data sets, the Gorman-Toman 10 variable set (Hoerl and Kennard 1970b, p. 71) and the Hald 4 variable set (Draper and Smith 1966, p. 366). The former has been used in a number of papers on ridge regression (Mallows 1973, Marquardt and Snee 1975, Obenchain 1975, and Vinod 1976), and the latter is an excellent example of severe multicollinearity. The computer output generated by these example data sets is found in appendix B.

## Analysis of the Gorman-Toman Data

Since this data set was presented in the form of a correlation matrix, we used it directly as a moment matrix punched in REX format. The normal coefficients are identical to the standardized coefficients because a correlation matrix was used as input. The regression was specified as unweighted and through the mean with matrix input from tape 10 (see sample output, p. 13).

For the least-squares solution (see sample output, p. 13), the maximum VIF was just under 10, so one would expect a fairly low $k$ value. Marquardt's criterion is satisfied for all $k$ values less than 0.2 (see p. 14-17) but we would select $k = 0.04$ as this is the maximum $k$ value in that range for which the minimum VIF is still greater than one. This ridged solution has reduced the maximum VIF by 58 percent with only a 9 percent increase in the RSS relative to least-squares. Hoerl and Kennard (1970b) selected $k$ between 0.2 and 0.3 using the ridge trace. We would conclude that their approach leads to overestimation of the amount of bias necessary to stabilize the system. Note that the default selection of $k$ values was truncated at $k = 0.2$ as the maximum VIF fell under 1.0.

## Analysis of the Hald Data

In this example, the raw data (13 observations) were read from cards and punched moment matrix output was requested (see sample output, p. 19). The data were weighted by 1.0, to show the change in labeling, and were used untransformed by TRNX.

This data set was severely multicollinear as indicated by a maximum VIF of 282 for the least-squares solution (see p. 20). Using our modified Marquardt criterion, we selected $k = 0.03$ which reduced the maximum VIF by over 99 percent with a 30 percent increase in RSS. $\overline{R}^2$ decreased less than 2 percent. The determinant of $X'X$ has increased more than 10 times indicating the gain in stability.

The second problem set (see p. 24-25) in this run used only the variables 1 and 2 for prediction. The data matrix from the first problem is used with three selected $k$ values, 0.11, 0.13, and 0.15. The least-squares solution is almost orthogonal with both minimum and maximum VIF's barely larger than one. Ridging is obviously unnecessary, and those solutions are truncated after the first two $k$ values.

Note that indicators for weighting and for an intercept are repeated (see p. 24) so that the problem is correctly labeled. However, the indicators have no effect on the solution.

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# APPENDIX A

## Programing Notes

The main program, BREX, interprets the control cards for each problem set. If raw data are input, subroutine MTRX is called to read them using subroutine TRNX to generate variables for the regressions. MTRX also produces punched output of the moment matrix in vector *S*, identical to that of REX, if requested. The elements of *S* are corrected for the mean if IMO = 0 and the weights are adjusted to sum to the number of observations BREX then creates the correlation matrix for the model specified on control card 3 from the vector *S*. The standardized least-squares solution is found by inverting the correlation matrix using subroutine NVRT. Gauss-Jordan elimination with column pivoting to maximize the pivot elements is the technique used. The inversion is performed in double precision on the scaled (correlation) form of the matrix to achieve a minimum of rounding error (Deegan 1976). As a check for numerical singularity, the determinant of $X'X$ is output.

The normal regression coefficients and their variances are obtained from the standardized solution (Draper and Smith 1966). The estimates of the MSE, ESS, and adjusted $R^2$ ($\bar{R}^2$) are all based on the normalized solution.

The ridged solutions are calculated in a similar manner, first adding $k$ to the diagonal of the correlation matrix. Since the residuals are not available from matrix input, the RSS is calculated by

$$\mathrm{RSS}(k) = Y'Y - (B^*)'X'Y - k(B^*)'B^* \qquad (13)$$

as given by Hoerl and Kennard (1970a).

# APPENDIX B

## Card Deck Setup and Output Generated by Example Data Sets

## Card Deck Setup for Gorman-Toman Data (CDC's Scope or NOS / BE Operating Systems)

CM60000 on the job card indicates that, at most, 60,000 (octal) words of memory are required to run this program. The zeros on BREX control card 2 need not be punche as a blank is read as a zero.

```
JOBNAME,CM60000.
ATTACH(TAPE10,GTDATA,ID=MITCH)
REWIND(TAPE10)
FORTRAN.
LGO.
*EOR  (end of record card)
  (followed by the FORTRAN source deck BREX and subroutines MTRX and NVRT)
SUBROUTINE TRNX
COMMON/RMT/X
COMMON/MT/D,W
DIMENSION  D(50), X(50)
RETURN
END
*EOR
    GORMAN TOMAN  TEN FACTOR PROBLEM
   11   10    0    0    0   10   0          0    0   0
XXXXXXXXXXY
blank card
blank card
blank card
DONE
*EOF  (end of file card)
```

```
   GORMAN TOMAN  TEN FACTOR PROBLEM

  UNWEIGHTED REGRESSION THRU THE MEAN    USING REX DATA

  NO. OF VARIABLES READ IN = 11 ON CARDS


  VARIABLES IN REGRESSION

                1    1    2    2    3    3    4    4    5
           5    0    5    0    5    0    5    0    5    0
  ====XXXXXXXXXXY


  DEFAULT SELECTION OF K VALUES REQUESTED




LEAST-SQUARES SOLUTION


MSE     =  4.1308E-03          DETERMINANT =  3.9954E-03

MAX VIF =  9.3315E+00          RESIDUAL SS =  1.0327E-01

MIN VIF =  1.1589E+00          RBARSQ      =  8.5542E-01


REGRESSOR          NORMAL             VARIANCE           STANDARDIZED
VARIABLE         REGRESSION          OF NORMAL            REGRESSION
SUBSCRIPT       COEFFICIENTS        COEFFICIENTS         COEFFICIENTS

    1           -1.8504850E-01      2.1227045E-02      -1.8504850E-01
    2           -2.2144353E-01      6.9481955E-03      -2.2144353E-01
    3           -3.5946180E-01      9.1378250E-03      -3.5946180E-01
    4           -1.0541815E-01      4.7873375E-03      -1.0541815E-01
    5           -4.6891860E-01      2.5177717E-02      -4.6891860E-01
    6            8.1316918E-01      3.8546446E-02       8.1316918E-01
    7            2.8474318E-01      1.0008915E-02       2.8474318E-01
    8            3.8337884E-01      8.5157305E-03       3.8337884E-01
    9            9.2058062E-02      5.4828320E-03       9.2058062E-02
   10            9.4442659E-02      9.8932603E-03       9.4442659E-02
    U             .0                                     .0
```

```
        GORMAN TOMAN  TEN FACTOR PROBLEM

        RIDGED (BIASED) SOLUTIONS


K         =  5.0000E-03          DETERMINANT =  4.7150E-03        K         =  1.0000E-02          DETERMINANT =  5.5280E-03

MAX VIF =  8.1445E+00            RESIDUAL SS =  1.0353E-01        MAX VIF =  7.1765E+00            RESIDUAL SS =  1.0421E-01

MIN VIF =  1.1375E+00            RBARSQ      =  8.5505E-01        MIN VIF =  1.1173E+00            RBARSQ      =  8.5411E-01

REGRESSOR      NORMAL          VARIANCE       STANDARDIZED        REGRESSOR      NORMAL          VARIANCE       STANDARDIZED
VARIABLE     REGRESSION        OF NORMAL       REGRESSION         VARIABLE     REGRESSION        OF NORMAL       REGRESSION
SUBSCRIPT    COEFFICIENTS     COEFFICIENTS     COEFFICIENTS       SUBSCRIPT    COEFFICIENTS     COEFFICIENTS     COEFFICIENTS


    1        -2.0125588E-01   1.9336351E-02  -2.0125588E-01           1        -2.1489941E-01   1.7732604E-02  -2.1489941E-01
    2        -2.1398027E-01   6.6957033E-03  -2.1398027E-01           2        -2.0732151E-01   6.4677241E-03  -2.0732151E-01
    3        -3.5499681E-01   8.8507526E-03  -3.5499681E-01           3        -3.5069034E-01   8.5794495E-03  -3.5069034E-01
    4        -1.0223073E-01   4.6986361E-03  -1.0223073E-01           4        -9.9365396E-02   4.6155381E-03  -9.9365396E-02
    5        -4.3718196E-01   2.2880809E-02  -4.3718196E-01           5        -4.0902430E-01   2.0930306E-02  -4.0902430E-01
    6         7.7006222E-01   3.3643492E-02   7.7006222E-01           6         7.3262822E-01   2.9644613E-02   7.3262822E-01
    7         2.6901578E-01   9.4527598E-03   2.6901578E-01           7         2.5493465E-01   8.9675271E-03   2.5493465E-01
    8         3.7743756E-01   8.2087548E-03   3.7743756E-01           8         3.7193814E-01   7.9254569E-03   3.7193814E-01
    9         9.6559720E-02   5.3213082E-03   9.6559720E-02           9         1.0045223E-01   5.1751752E-03   1.0045223E-01
   10         9.8200681E-02   9.5458876E-03   9.8200681E-02          10         1.0146399E-01   9.2213807E-03   1.0146399E-01
    U          .0                              .0                     U          .0                              .0

        RIDGED (BIASED) SOLUTIONS


K         =  2.0000E-02          DETERMINANT =  7.4706E-03        K         =  3.0000E-02          DETERMINANT =  9.9027E-03

MAX VIF =  5.7072E+00            RESIDUAL SS =  1.0630E-01        MAX VIF =  4.6596E+00            RESIDUAL SS =  1.0890E-01

MIN VIF =  1.0804E+00            RBARSQ      =  8.5118E-01        MIN VIF =  1.0471E+00            RBARSQ      =  8.4754E-01

REGRESSOR      NORMAL          VARIANCE       STANDARDIZED        REGRESSOR      NORMAL          VARIANCE       STANDARDIZED
VARIABLE     REGRESSION        OF NORMAL       REGRESSION         VARIABLE     REGRESSION        OF NORMAL       REGRESSION
SUBSCRIPT    COEFFICIENTS     COEFFICIENTS     COEFFICIENTS       SUBSCRIPT    COEFFICIENTS     COEFFICIENTS     COEFFICIENTS


    1        -2.3635977E-01   1.5161208E-02  -2.3635977E-01           1        -2.5218034E-01   1.3192863E-02  -2.5218034E-01
    2        -1.9589621E-01   6.0692427E-03  -1.9589621E-01           2        -1.8638641E-01   5.7293226E-03  -1.8638641E-01
    3        -3.4253233E-01   8.0793245E-03  -3.4253233E-01           3        -3.3494131E-01   7.6289630E-03  -3.3494131E-01
    4        -9.4395176E-02   4.4630568E-03  -9.4395176E-02           4        -9.0199323E-02   4.3252462E-03  -9.0199323E-02
    5        -3.6114761E-01   1.7798997E-02  -3.6114761E-01           5        -3.2183073E-01   1.5399404E-02  -3.2183073E-01
    6         6.7086778E-01   2.3575393E-02   6.7086778E-01           6         6.2206816E-01   1.9248003E-02   6.2206816E-01
    7         2.3067894E-01   8.1567040E-03   2.3067894E-01           7         2.1042125E-01   7.5006885E-03   2.1042125E-01
    8         3.6198113E-01   7.4181487E-03   3.6198113E-01           8         3.5308820E-01   6.9753570E-03   3.5308820E-01
    9         1.0679811E-01   4.9193724E-03   1.0679811E-01           9         1.1168298E-01   4.7009305E-03   1.1168298E-01
   10         1.0682439E-01   8.6311054E-03   1.0682439E-01          10         1.1100280E-01   8.1067405E-03   1.1100280E-01
    U          .0                              .0                     U          .0                              .0
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       GORMAN TOMAN  TEN FACTOR PROBLEM

      RIDGED (BIASED) SOLUTIONS

K          =  4.0000E-02          DETERMINANT =  1.2915E-02                 K          =  5.0000E-02          DETERMINANT =  1.6610E-02

MAX VIF =  3.8857E+00          RESIDUAL SS =  1.1172E-01                 MAX VIF =  3.2971E+00          RESIDUAL SS =  1.1459E-01

MIN VIF =  1.0165E+00          RBARSQ      =  8.4360E-01                 MIN VIF =  9.8831E-01          RBARSQ      =  8.3958E-01

REGRESSOR      NORMAL          VARIANCE      STANDARDIZED               REGRESSOR      NORMAL          VARIANCE      STANDARDIZED
VARIABLE     REGRESSION       OF NORMAL       REGRESSION                VARIABLE     REGRESSION       OF NORMAL       REGRESSION
SUBSCRIPT   COEFFICIENTS     COEFFICIENTS    COEFFICIENTS               SUBSCRIPT   COEFFICIENTS     COEFFICIENTS    COEFFICIENTS


    1        -2.6406036E-01   1.1640049E-02  -2.6406036E-01                 1        -2.7310025E-01   1.0385666E-02  -2.7310025E-01
    2        -1.7829442E-01   5.4335251E-03  -1.7829442E-01                 2        -1.7128685E-01   5.1723008E-03  -1.7128685E-01
    3        -3.2786825E-01   7.2214413E-03  -3.2786825E-01                 3        -3.2126607E-01   6.8510528E-03  -3.2126607E-01
    4        -8.6581606E-02   4.1990928E-03  -8.6581606E-02                 4        -8.3410475E-02   4.0825087E-03  -8.3410475E-02
    5        -2.8885650E-01   1.3505543E-02  -2.8885650E-01                 5        -2.6073167E-01   1.1975855E-02  -2.6073167E-01
    6         5.8257458E-01   1.6050971E-02   5.8257458E-01                 6         5.4997853E-01   1.3619818E-02   5.4997853E-01
    7         1.9316162E-01   6.9548119E-03   1.9316162E-01                 7         1.7822368E-01   6.4908692E-03   1.7822368E-01
    8         3.4499789E-01   6.5842768E-03   3.4499789E-01                 8         3.3753830E-01   6.2355812E-03   3.3753830E-01
    9         1.1548683E-01   4.5106075E-03   1.1548683E-01                 9         1.1846770E-01   4.3421565E-03   1.1846770E-01
   10         1.1430727E-01   7.6370651E-03   1.1430727E-01                10         1.1694606E-01   7.2136166E-03   1.1694606E-01
    U          .0                              .0                           U          .0                              .0

      RIDGED (BIASED) SOLUTIONS

K          =  6.0000E-02          DETERMINANT =  2.1105E-02                 K          =  7.0000E-02          DETERMINANT =  2.6533E-02

MAX VIF =  2.8387E+00          RESIDUAL SS =  1.1745E-01                 MAX VIF =  2.4744E+00          RESIDUAL SS =  1.2025E-01

MIN VIF =  9.6203E-01          RBARSQ      =  8.3557E-01                 MIN VIF =  9.3743E-01          RBARSQ      =  8.3165E-01

REGRESSOR      NORMAL          VARIANCE      STANDARDIZED               REGRESSOR      NORMAL          VARIANCE      STANDARDIZED
VARIABLE     REGRESSION       OF NORMAL       REGRESSION                VARIABLE     REGRESSION       OF NORMAL       REGRESSION
SUBSCRIPT   COEFFICIENTS     COEFFICIENTS    COEFFICIENTS               SUBSCRIPT   COEFFICIENTS     COEFFICIENTS    COEFFICIENTS


    1        -2.8004042E-01   9.3528089E-03  -2.8004042E-01                 1        -2.8539501E-01   8.4888576E-03  -2.8539501E-01
    2        -1.6513114E-01   4.9389754E-03  -1.6513114E-01                 2        -1.5965951E-01   4.7286764E-03  -1.5965951E-01
    3        -3.1509129E-01   6.5130527E-03  -3.1509129E-01                 3        -3.0930449E-01   6.2034638E-03  -3.0930449E-01
    4        -8.0593967E-02   3.9739733E-03  -8.0593967E-02                 4        -7.8065519E-02   3.8723358E-03  -7.8065519E-02
    5        -2.3641005E-01   1.0717087E-02  -2.3641005E-01                 5        -2.1513455E-01   9.6652580E-03  -2.1513455E-01
    6         5.2262982E-01   1.1726256E-02   5.2262982E-01                 6         4.9936096E-01   1.0221342E-02   4.9936096E-01
    7         1.6513084E-01   6.0900413E-03   1.6513084E-01                 7         1.5353590E-01   5.7391955E-03   1.5353590E-01
    8         3.3059118E-01   5.9222325E-03   3.3059118E-01                 8         3.2407194E-01   5.6387753E-03   3.2407194E-01
    9         1.2080767E-01   4.1911641E-03   1.2080767E-01                 9         1.2263927E-01   4.0544030E-03   1.2263927E-01
   10         1.1906577E-01   6.8297742E-03   1.1906577E-01                10         1.2077296E-01   6.4802205E-03   1.2077296E-01
    U          .0                              .0                           U          .0                              .0
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     GORMAN TOMAN  TEN FACTOR PROBLEM

     RIDGED (BIASED) SOLUTIONS

K        =  8.0000E-02        DETERMINANT =  3.3041E-02          K        =  9.0000E-02         DETERMINANT =  4.0796E-02

MAX VIF =  2.1798E+00        RESIDUAL SS =  1.2299E-01          MAX VIF =  1.9399E+00         RESIDUAL SS =  1.2565E-01

MIN VIF =  9.1428E-01        RBARSQ      =  8.2782E-01          MIN VIF =  8.9240E-01         RBARSQ      =  8.2410E-01

REGRESSOR     NORMAL          VARIANCE     STANDARDIZED         REGRESSOR     NORMAL          VARIANCE     STANDARDIZED
VARIABLE    REGRESSION        OF NORMAL     REGRESSION          VARIABLE    REGRESSION        OF NORMAL     REGRESSION
SUBSCRIPT   COEFFICIENTS    COEFFICIENTS   COEFFICIENTS         SUBSCRIPT   COEFFICIENTS    COEFFICIENTS   COEFFICIENTS


    1      -2.8953059E-01  7.7565789E-03  -2.8953059E-01            1      -2.9271455E-01  7.1288758E-03  -2.9271455E-01
    2      -1.5474751E-01  4.5377214E-03  -1.5474751E-01            2      -1.5030057E-01  4.3632497E-03  -1.5030057E-01
    3      -3.0387032E-01  5.9189283E-03  -3.0387032E-01            3      -2.9875714E-01  5.6565924E-03  -2.9875714E-01
    4      -7.5775520E-02  3.7766988E-03  -7.5775520E-02            4      -7.3686063E-02  3.6863454E-03  -7.3686063E-02
    5      -1.9634223E-01  8.7749804E-03  -1.9634223E-01            5      -1.7960487E-01  8.0131456E-03  -1.7960487E-01
    6       4.7932343E-01  9.0045110E-03   4.7932343E-01            6       4.6188623E-01  8.0058522E-03   4.6188623E-01
    7       1.4317867E-01  5.4288226E-03   1.4317867E-01            7       1.3385954E-01  5.1518234E-03   1.3385954E-01
    8       3.1791803E-01  5.3808899E-03   3.1791803E-01            8       3.1208175E-01  5.1450959E-03   3.1208175E-01
    9       1.2406154E-01  3.9294465E-03   1.2406154E-01            9       1.2515006E-01  3.8144284E-03   1.2515006E-01
   10       1.2214723E-01  6.1606018E-03   1.2214723E-01           10       1.2324938E-01  5.8673001E-03   1.2324938E-01
    U        .0                             .0                      U        .0                             .0

     RIDGED (BIASED) SOLUTIONS

K        =  1.0000E-01        DETERMINANT =  4.9984E-02          K        =  1.2000E-01         DETERMINANT =  7.3516E-02

MAX VIF =  1.7805E+00        RESIDUAL SS =  1.2823E-01          MAX VIF =  1.5200E+00         RESIDUAL SS =  1.3316E-01

MIN VIF =  8.7167E-01        RBARSQ      =  8.2048E-01          MIN VIF =  8.3316E-01         RBARSQ      =  8.1357E-01

REGRESSOR     NORMAL          VARIANCE     STANDARDIZED         REGRESSOR     NORMAL          VARIANCE     STANDARDIZED
VARIABLE    REGRESSION        OF NORMAL     REGRESSION          VARIABLE    REGRESSION        OF NORMAL     REGRESSION
SUBSCRIPT   COEFFICIENTS    COEFFICIENTS   COEFFICIENTS         SUBSCRIPT   COEFFICIENTS    COEFFICIENTS   COEFFICIENTS


    1      -2.9514574E-01  6.5855541E-03  -2.9514574E-01            1      -2.9831672E-01  5.6940929E-03  -2.9831672E-01
    2      -1.4624535E-01  4.2029877E-03  -1.4624535E-01            2      -1.3909004E-01  3.9180606E-03  -1.3909004E-01
    3      -2.9393673E-01  5.4140159E-03  -2.9393673E-01            3      -2.8507613E-01  4.9800304E-03  -2.8507613E-01
    4      -7.1767557E-02  3.6006919E-03  -7.1767557E-02            4      -6.8353783E-02  3.4416300E-03  -6.8353783E-02
    5      -1.6459023E-01  7.3550291E-03  -1.6459023E-01            5      -1.3873261E-01  6.2788355E-03  -1.3873261E-01
    6       4.4657076E-01  7.1755274E-03   4.4657076E-01            6       4.2090765E-01  5.8839502E-03   4.2090765E-01
    7       1.2542218E-01  4.9027609E-03   1.2542218E-01            7       1.1071842E-01  4.4722940E-03   1.1071842E-01
    8       3.0652582E-01  4.9285479E-03   3.0652582E-01            8       2.9614105E-01  4.5441562E-03   2.9614105E-01
    9       1.2596360E-01  3.7078856E-03   1.2596360E-01            9       1.2694213E-01  3.5157858E-03   1.2694213E-01
   10       1.2412672E-01  5.5972728E-03   1.2412672E-01           10       1.2534929E-01  5.1170799E-03   1.2534929E-01
    U        .0                             .0                      U        .0                             .0
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GORMAN TOMAN  TEN FACTOR PROBLEM

RIDGED (BIASED) SOLUTIONS

K        =  1.5000E-01        DETERMINANT =  1.2557E-01          K        =  2.0000E-01        DETERMINANT =  2.7982E-01

MAX VIF  =  1.2317E+00        RESIDUAL SS =  1.4008E-01          MAX VIF  =  9.1545E-01        RESIDUAL SS =  1.5056E-01

MIN VIF  =  7.8155E-01        RBARSQ      =  8.0389E-01          MIN VIF  =  7.0807E-01        RBARSQ      =  7.8922E-01

REGRESSOR      NORMAL          VARIANCE      STANDARDIZED        REGRESSOR      NORMAL          VARIANCE      STANDARDIZED
VARIABLE     REGRESSION       OF NORMAL       REGRESSION         VARIABLE     REGRESSION       OF NORMAL       REGRESSION
SUBSCRIPT   COEFFICIENTS     COEFFICIENTS    COEFFICIENTS        SUBSCRIPT   COEFFICIENTS     COEFFICIENTS    COEFFICIENTS

    1      -3.0023079E-01  4.7010419E-03  -3.0023079E-01             1      -2.9925647E-01  3.5987492E-03  -2.9925647E-01
    2      -1.3016786E-01  3.5604640E-03  -1.3016786E-01             2      -1.1854596E-01  3.0950444E-03  -1.1854596E-01
    3      -2.7343191E-01  4.4331081E-03  -2.7343191E-01             3      -2.5739977E-01  3.7241707E-03  -2.5739977E-01
    4      -6.4052924E-02  3.2284178E-03  -6.4052924E-02             4      -5.8403030E-02  2.9248868E-03  -5.8403030E-02
    5      -1.0776736E-01  5.0877874E-03  -1.0776736E-01             5      -6.9909196E-02  3.7815227E-03  -6.9909196E-02
    6       3.9130329E-01  4.5529624E-03   3.9130329E-01             6       3.5653716E-01  3.2159147E-03   3.5653716E-01
    7       9.2827477E-02  3.9537111E-03   9.2827477E-02             7       7.0583670E-02  3.3139143E-03   7.0583670E-02
    8       2.8207215E-01  4.0640363E-03   2.8207215E-01             8       2.6173571E-01  3.4460609E-03   2.6173571E-01
    9       1.2724922E-01  3.2683124E-03   1.2724922E-01             9       1.2590888E-01  2.9315614E-03   1.2590888E-01
   10       1.2622555E-01  4.5175468E-03   1.2622555E-01            10       1.2614206E-01  3.7509075E-03   1.2614206E-01
    U        .0                             .0                       U        .0                             .0
```

# Card Deck Setup for Hald Data Using a Binary Version of BREX
## (CDC's or NOS / BE Operating Systems)

This example uses a binary (compiled) version of BREX and subroutines NVRT and MTRX, which reside on the permanent file BINARYBREX. A source deck of TRNX is used because it must be adjusted to suit a given run.

```
  JOBNAME, CM60000.
  ATTACH(BREX, BINARYBREX,ID=MITCH)
  REWIND(BREX)
  FORTRAN.
  LOAD(LGO)
  BREX.
  *EOR  (end of record card)
  SUBROUTINE TRNX
  COMMON/RMT/X
  COMMON/MT/D,W
  DIMENSION  D(50), X(50)
  DO 1 J = 1,5
1 X(J) = D(J)
  W = 1.0
  RETURN
  END
  *EOR
      DATA FROM HALD GIVEN BY DRAPER AND SMITH (1966) P.395
      5    4    0    0    0    0    1        13    5    7
  XXXXY
  blank card
  (4F3.0,F6.1)
  blank card
    7 26  6 60  78.5
    1 29 15 52  74.3
    .  .  .  .   .
    .  .  .  .   .
    .  .  .  .   .
   10 68  8 12 109.4
      DATA FROM HALD GIVEN BY DRAPER AND SMITH (1966) P.375
      5    2    3    1    0    0    1         0    0    0
  XX  Y
    0.11    0.13    0.15
  blank card
  blank card
  DONE
  *EOF   (end of file card)
```

```
DATA FROM HALD GIVEN BY DRAPER AND SMITH (1966) P.395

WEIGHTED REGRESSION THRU THE MEAN    USING RAW DATA

NO. OF VARIABLES READ IN =  5 ON CARDS


VARIABLES IN REGRESSION

             1    1    2    2    3    3    4    4    5
        5    0    5    0    5    0    5    0    5    0
****XXXXYW


DEFAULT SELECTION OF K VALUES REQUESTED


DATA INPUT FORMAT
(4F3.0,F6.1)



LISTING OF FIRST TWO OBSERVATION VECTORS (AFTER TRANSFORMATIONS, IF ANY)


7.0000000E+00 2.6000000E+01 6.0000000E+00 6.0000000E+01 7.8500000E+01 1.0000000E+00
1.0000000E+00 2.9000000E+01 1.5000000E+01 5.2000000E+01 7.4300000E+01 1.0000000E+00


LAST OBSERVATION VECTOR----IF ABSENT, INCORRECT NO. OF OBS OR FORMAT


1.0000000E+01 6.8000000E+01 8.0000000E+00 1.2000000E+01 1.0940000E+02 1.0000000E+00
```

```
    DATA FROM HALD GIVEN BY DRAPER AND SMITH (1966) P.395

    LEAST-SQUARES SOLUTION

    MSE     =  5.9830E+00         DETERMINANT =  1.0677E-03

    MAX VIF =  2.8251E+02         RESIDUAL SS =  4.7864E+01

    MIN VIF =  3.8496E+01         RBARSQ      =  9.7356E-01

REGRESSOR         NORMAL            VARIANCE          STANDARDIZED
VARIABLE        REGRESSION         OF NORMAL           REGRESSION
SUBSCRIPT       COEFFICIENTS      COEFFICIENTS        COEFFICIENTS

    1           1.5511026E+00     5.5468215E-01       6.0651195E-01
    2           5.1016758E-01     5.2386907E-01       5.2770563E-01
    3           1.0190940E-01     5.6958574E-01       4.3389698E-02
    4          -1.4406103E-01     5.0275483E-01      -1.6028742E-01
    U           6.2405369E+01                          .0

     RIDGED (BIASED) SOLUTIONS

K       =  5.0000E-03        DETERMINANT =  4.4962E-03          K       =  1.0000E-02          DETERMINANT =  8.1399E-03

MAX VIF =  1.7405E+01        RESIDUAL SS =  4.8287E+01          MAX VIF =  5.9488E+00          RESIDUAL SS =  4.8527E+01

MIN VIF =  4.7340E+00        RBARSQ      =  9.7333E-01          MIN VIF =  3.1275E+00          RBARSQ      =  9.7320E-01

REGRESSOR      NORMAL         VARIANCE      STANDARDIZED        REGRESSOR      NORMAL         VARIANCE      STANDARDIZED
VARIABLE     REGRESSION      OF NORMAL       REGRESSION         VARIABLE     REGRESSION      OF NORMAL       REGRESSION
SUBSCRIPT    COEFFICIENTS    COEFFICIENTS    COEFFICIENTS       SUBSCRIPT    COEFFICIENTS    COEFFICIENTS    COEFFICIENTS

    1        1.3551314E+00  6.8210719E-02   5.2988329E-01           1        1.3152096E+00  4.5587520E-02   5.1427310E-01
    2        3.3002834E-01  3.2933221E-02   3.4137373E-01           2        3.0611536E-01  1.1685307E-02   3.1663870E-01
    3       -9.3299737E-02  6.1180586E-02  -3.9723983E-02           3       -1.2901810E-01  3.8007597E-02  -5.4931695E-02
    4       -3.2009801E-01  3.0974122E-02  -3.5615241E-01           4       -3.4293876E-01  1.0586404E-02  -3.8156584E-01
    U        8.0120585E+01                   .0                     U        8.2675564E+01                   .0
```

```
      DATA FROM HALD GIVEN BY DRAPER AND SMITH (1966) P.395

      RIDGED (BIASED) SOLUTIONS

K          =  2.0000E-02          DETERMINANT =  1.6084E-02          K          =  3.0000E-02          DETERMINANT =  2.4926E-02

MAX VIF =  2.4564E+00          RESIDUAL SS =  4.9073E+01          MAX VIF =  2.1661E+00          RESIDUAL SS =  4.9812E+01

MIN VIF =  2.0152E+00          RBARSQ      =  9.7290E-01          MIN VIF =  1.1506E+00          RBARSQ      =  9.7249E-01

REGRESSOR      NORMAL          VARIANCE      STANDARDIZED      REGRESSOR      NORMAL          VARIANCE      STANDARDIZED
VARIABLE     REGRESSION       OF NORMAL       REGRESSION       VARIABLE     REGRESSION       OF NORMAL       REGRESSION
SUBSCRIPT   COEFFICIENTS    COEFFICIENTS    COEFFICIENTS       SUBSCRIPT   COEFFICIENTS    COEFFICIENTS    COEFFICIENTS

    1        1.2722658E+00  3.5392970E-02   4.9748122E-01          1        1.2413443E+00  3.1211060E-02   4.8539028E-01
    2        2.9318939E-01  4.3406424E-03   3.0326837E-01          2        2.8972330E-01  2.6871716E-03   2.9968313E-01
    3       -1.6304659E-01  2.8226964E-02  -6.9419919E-02          3       -1.8517787E-01  2.4617229E-02  -7.8842696E-02
    4       -3.5429372E-01  3.5861906E-03  -3.9419977E-01          4       -3.5624450E-01  2.0476469E-03  -3.9637028E-01
    U        8.4359564E+01                   .0                    U        8.5076184E+01                   .0
      RIDGED (BIASED) SOLUTIONS

K          =  4.0000E-02          DETERMINANT =  3.4689E-02          K          =  5.0000E-02          DETERMINANT =  4.5398E-02

MAX VIF =  1.9668E+00          RESIDUAL SS =  5.0734E+01          MAX VIF =  1.8077E+00          RESIDUAL SS =  5.1815E+01

MIN VIF =  8.2047E-01          RBARSQ      =  9.7198E-01          MIN VIF =  6.5617E-01          RBARSQ      =  9.7138E-01

REGRESSOR      NORMAL          VARIANCE      STANDARDIZED      REGRESSOR      NORMAL          VARIANCE      STANDARDIZED
VARIABLE     REGRESSION       OF NORMAL       REGRESSION       VARIABLE     REGRESSION       OF NORMAL       REGRESSION
SUBSCRIPT   COEFFICIENTS    COEFFICIENTS    COEFFICIENTS       SUBSCRIPT   COEFFICIENTS    COEFFICIENTS    COEFFICIENTS

    1        1.2151068E+00  2.8338752E-02   4.7513091E-01          1        1.1917230E+00  2.6047364E-02   4.6598736E-01
    2        2.8867933E-01  2.0300200E-03   2.9860327E-01          2        2.8850399E-01  1.6856488E-03   2.9842190E-01
    3       -2.0287118E-01  2.2278740E-02  -8.6375926E-02          3       -2.1796008E-01  2.0465513E-02  -9.2800290E-02
    4       -3.5571091E-01  1.4601020E-03  -3.9577659E-01          4       -3.5423280E-01  1.1677159E-03  -3.9413199E-01
    U        8.5514455E+01                   .0                    U        8.5830620E+01                   .0
```

```
      DATA FROM HALD GIVEN BY DRAPER AND SMITH (1966) P.395

      RIDGED (BIASED) SOLUTIONS

K        =  6.0000E-02          DETERMINANT =  5.7078E-02          K        =  7.0000E-02          DETERMINANT =  6.9755E-02

MAX VIF  =  1.6736E+00          RESIDUAL SS =  5.3034E+01          MAX VIF  =  1.5575E+00          RESIDUAL SS =  5.4371E+01

MIN VIF  =  5.6025E-01          RBARSQ      =  9.7071E-01          MIN VIF  =  4.9788E-01          RBARSQ      =  9.6997E-01

REGRESSOR       NORMAL         VARIANCE      STANDARDIZED          REGRESSOR       NORMAL         VARIANCE      STANDARDIZED
VARIABLE      REGRESSION       OF NORMAL      REGRESSION           VARIABLE      REGRESSION       OF NORMAL      REGRESSION
SUBSCRIPT    COEFFICIENTS    COEFFICIENTS    COEFFICIENTS          SUBSCRIPT    COEFFICIENTS    COEFFICIENTS    COEFFICIENTS


    1          1.1704313E+00  2.4114651E-02   4.5766190E-01            1          1.1508131E+00  2.2441313E-02   4.4999079E-01
    2          2.8867296E-01  1.4726538E-03   2.9859669E-01            2          2.8896914E-01  1.3258173E-03   2.9890304E-01
    3         -2.3119084E-01  1.8958139E-02  -9.8433514E-02            3         -2.4296415E-01  1.7663335E-02  -1.0344620E-01
    4         -3.5233834E-01  9.9701344E-04  -3.9202415E-01            4         -3.5025225E-01  8.8601568E-04  -3.8970309E-01
    U          8.6080234E+01                    .0                     U          8.6288334E+01                    .0

      RIDGED (BIASED) SOLUTIONS

K        =  8.0000E-02          DETERMINANT =  8.3454E-02          K        =  9.0000E-02          DETERMINANT =  9.8201E-02

MAX VIF  =  1.4554E+00          RESIDUAL SS =  5.5813E+01          MAX VIF  =  1.3649E+00          RESIDUAL SS =  5.7348E+01

MIN VIF  =  4.5406E-01          RBARSQ      =  9.6917E-01          MIN VIF  =  4.2143E-01          RBARSQ      =  9.6833E-01

REGRESSOR       NORMAL         VARIANCE      STANDARDIZED          REGRESSOR       NORMAL         VARIANCE      STANDARDIZED
VARIABLE      REGRESSION       OF NORMAL      REGRESSION           VARIABLE      REGRESSION       OF NORMAL      REGRESSION
SUBSCRIPT    COEFFICIENTS    COEFFICIENTS    COEFFICIENTS          SUBSCRIPT    COEFFICIENTS    COEFFICIENTS    COEFFICIENTS


    1          1.1325960E+00  2.0970851E-02   4.4286754E-01            1          1.1155836E+00  1.9665904E-02   4.3621533E-01
    2          2.8929203E-01  1.2167696E-03   2.9923703E-01            2          2.8959250E-01  1.1314068E-03   2.9954783E-01
    3         -2.5353510E-01  1.6530643E-02  -1.0794697E-01            3         -2.6308444E-01  1.5528094E-02  -1.1201277E-01
    4         -3.4808308E-01  8.0802842E-04  -3.8728960E-01            4         -3.4588760E-01  7.4996617E-04  -3.8484682E-01
    U          8.6468050E+01                    .0                     U          8.6627044E+01                    .0
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       DATA FROM HALD GIVEN BY DRAPER AND SMITH (1966) P.395

       RIDGED (BIASED) SOLUTIONS

K        =  1.0000E-01          DETERMINANT =  1.1402E-01                K        =  1.2000E-01          DETERMINANT =  1.4899E-01

MAX VIF  =  1.2839E+00          RESIDUAL SS =  5.8967E+01                MAX VIF  =  1.1453E+00          RESIDUAL SS =  6.2428E+01

MIN VIF  =  3.9603E-01          RBARSQ      =  9.6743E-01                MIN VIF  =  3.5859E-01          RBARSQ      =  9.6552E-01

REGRESSOR       NORMAL          VARIANCE       STANDARDIZED              REGRESSOR       NORMAL          VARIANCE       STANDARDIZED
VARIABLE      REGRESSION        OF NORMAL       REGRESSION               VARIABLE      REGRESSION        OF NORMAL       REGRESSION
SUBSCRIPT    COEFFICIENTS     COEFFICIENTS     COEFFICIENTS              SUBSCRIPT    COEFFICIENTS     COEFFICIENTS     COEFFICIENTS

    1          1.0996246E+00   1.8499396E-02   4.2997506E-01                 1          1.0704034E+00   1.6502951E-02   4.1854899E-01
    2          2.8984628E-01   1.0619790E-03   2.9981034E-01                 2          2.9017524E-01   9.5419632E-04   3.0015061E-01
    3         -2.7174930E-01   1.4633257E-02  -1.1570198E-01                 3         -2.8684109E-01   1.3103227E-02  -1.2212758E-01
    4         -3.4369689E-01   7.0476959E-04  -3.8240937E-01                 4         -3.3939198E-01   6.3813896E-04  -3.7761957E-01
    U          8.6770159E+01                    .0                           U          8.7020825E+01                    .0

       RIDGED (BIASED) SOLUTIONS

K        =  1.5000E-01          DETERMINANT =  2.1017E-01                K        =  2.0000E-01          DETERMINANT =  3.3721E-01

MAX VIF  =  9.8164E-01          RESIDUAL SS =  6.8100E+01                MAX VIF  =  7.8682E-01          RESIDUAL SS =  7.8622E+01

MIN VIF  =  3.2089E-01          RBARSQ      =  9.6239E-01                MIN VIF  =  2.8085E-01          RBARSQ      =  9.5657E-01

REGRESSOR       NORMAL          VARIANCE       STANDARDIZED              REGRESSOR       NORMAL          VARIANCE       STANDARDIZED
VARIABLE      REGRESSION        OF NORMAL       REGRESSION               VARIABLE      REGRESSION        OF NORMAL       REGRESSION
SUBSCRIPT    COEFFICIENTS     COEFFICIENTS     COEFFICIENTS              SUBSCRIPT    COEFFICIENTS     COEFFICIENTS     COEFFICIENTS

    1          1.0320312E+00   1.4144186E-02   4.0354469E-01                 1          9.7878945E-01   1.1337044E-02   3.8272612E-01
    2          2.9020376E-01   8.3893726E-04   3.0018010E-01                 2          2.8918811E-01   7.1099581E-04   2.9912954E-01
    3         -3.0501923E-01   1.1295281E-02  -1.2986724E-01                 3         -3.2678834E-01   9.1385108E-03  -1.3913581E-01
    4         -3.3321538E-01   5.7104445E-04  -3.7074726E-01                 4         -3.2371903E-01   4.9978694E-04  -3.6018129E-01
    U          8.7334413E+01                    .0                           U          8.7751900E+01                    .0
```

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DATA FROM HALD GIVEN BY DRAPER AND SMITH (1966) P.375

WEIGHTED REGRESSION THRU THE MEAN    USING     DATA FROM PREVIOUS PROBLEM

NO. OF VARIABLES READ IN =  5 ON CARDS


VARIABLES IN REGRESSION

             1    1    2    2    3    3    4    4    5
        5    0    5    0    5    0    5    0    5    0
====XX  Y

NO. OF K VALUES READ IN =  3




LEAST-SQUARES SOLUTION


MSE      =  5.7904E+00         DETERMINANT =  9.4775E-01

MAX VIF =  1.0551E+00         RESIDUAL SS =  5.7904E+01

MIN VIF =  1.0551E+00         RBARSQ      =  9.7441E-01

REGRESSOR          NORMAL              VARIANCE           STANDARDIZED
VARIABLE         REGRESSION           OF NORMAL            REGRESSION
SUBSCRIPT       COEFFICIENTS         COEFFICIENTS         COEFFICIENTS

    1          1.4683057E+00        1.4713914E-02        5.7413672E-01
    2          6.6225049E-01        2.1026555E-03        6.8501670E-01
    U          5.2577349E+01                              .0
```

```
DATA FROM HALD GIVEN BY DRAPER AND SMITH (1966) P.375

RIDGEC (BIASED) SOLUTIONS

K        =  1.1000E-01          DETERMINANT =  1.1799E+00          K        =  1.3000E-01          DETERMINANT =  1.2247E+00

MAX VIF =  8.3931E-01          RESIDUAL SS =  7.5967E+01          MAX VIF =  8.0750E-01          RESIDUAL SS =  8.2390E+01

MIN VIF =  8.3931E-01          RBARSQ      =  9.6643E-01          MIN VIF =  8.0750E-01          RBARSQ      =  9.6359E-01

REGRESSOR      NORMAL         VARIANCE      STANDARDIZED       REGRESSOR      NORMAL         VARIANCE      STANDARDIZED
VARIABLE     REGRESSION       OF NORMAL      REGRESSION        VARIABLE     REGRESSION       OF NORMAL      REGRESSION
SUBSCRIPT   COEFFICIENTS    COEFFICIENTS    COEFFICIENTS       SUBSCRIPT   COEFFICIENTS    COEFFICIENTS    COEFFICIENTS

    1      1.3536883E+00  1.1704247E-02  5.2931903E-01             1      1.3346868E+00  1.1260710E-02  5.2188905E-01
    2      6.0554453E-01  1.6725665E-03  6.2636136E-01             2      5.9627993E-01  1.6091839E-03  6.1677827E-01
    U      5.6163181E+01                  .0                       U      5.6751088E+01                  .0
```

Mitchell, Brian R., and David W. Hann.
1979. BREX: A computer program for applying ridge regression techniques to multiple linear regression. USDA For. Serv. Gen. Tech. Rep. INT-51, 25 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

An algorithm for ridge regression (BREX) is presented which can be used in conjunction with Grosenbaugh's REX (1967), a linear regression program with combinatorial screening. The algorithm uses either REX punched matrix input, or raw data with suitable transformations, to estimate ridged (biased) regression coefficients.

---

KEYWORDS: ridge regression, biased estimation, multicollinearity, linear regression, least-squares estimation, computer program

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KEYWORDS: ridge regression, biased estimation, multicollinearity, linear regression, least-squares estimation, computer program

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oc. INT 52

# AN ANNOTATED BIBLIOGRAPHY OF THE LARCH CASEBEARER (*Coleophora laricella* [Hübner])

Compiled by
**Robert E. Denton and**
**Leon J. Theroux**

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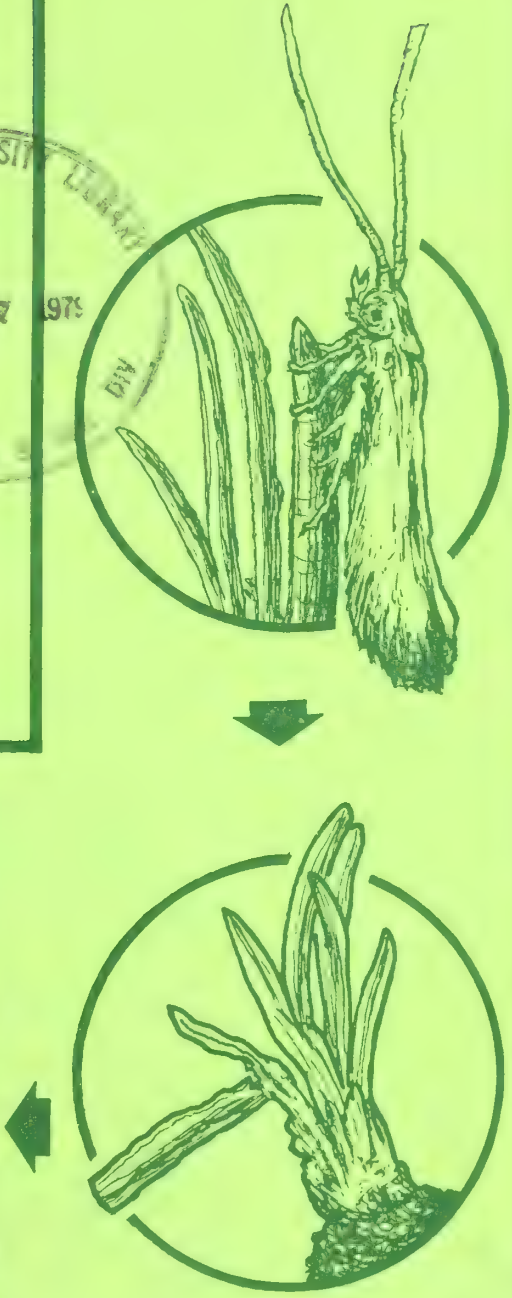

USDA FOREST SERVICE
GENERAL TECHNICAL REPORT INT-52

INTERMOUNTAIN FOREST AND
RANGE EXPERIMENT STATION
FOREST SERVICE
U.S. DEPARTMENT OF AGRICULTURE

# THE AUTHORS

ROBERT E. DENTON was principal entomologist at the Forestry Sciences Laboratory in Moscow, Idaho, when he retired from the USDA Forest Service in 1978. He received his B.S. degree in forestry at the New York State College of Forestry, Syracuse University, and his M.F. degree in forest entomology at the School of Natural Resources, University of Michigan. He joined the staff of the Bureau of Entomology and Plant Quarantine at Coeur d'Alene, Idaho, in 1950 and transferred to the Intermountain Forest and Range Experiment Station in 1953. His research has been directed primarily to the biology, ecology, and control of various defoliating insects including the spruce budworm and larch casebearer.

LEON J. THEROUX has been employed since 1971 as a biological technician on forest insect research at the Forestry Sciences Laboratory in Moscow, Idaho. He holds a B.S. degree in forestry from the University of Montana.

# ACKNOWLEDGMENTS

The authors gratefully acknowledge the technical reviews of the manuscript by Roger B. Ryan, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station; R. Ladd Livingston, Idaho Department of Lands; and Scott Tunnock, USDA Forest Service, Northern Region.

USDA Forest Service
General Technical Report INT-52
June 1979

# AN ANNOTATED BIBLIOGRAPHY OF THE LARCH CASEBEARER
## (*Coleophora laricella* [HÜBNER])

**Robert E. Denton and Leon J. Theroux**

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

# PREFACE

This bibliography is complete through 1977. Because many of the articles are in foreign languages and we were unable to have all of them translated, we relied on abstracting journals, such as the Review of Applied Entomology, to provide some of the annotations.

The results of initial surveys and studies of the larch casebearer in the western United States were commonly issued as unpublished reports. These reports are listed in the appendix.

# RESEARCH SUMMARY

The contents of 147 published references on the larch casebearer are annotated. Citations are cross-referenced by subject as well as by author. An appendix lists 30 unpublished reports.

# BIBLIOGRAPHY

1. AMMAN, GENE D., and SCOTT TUNNOCK. 1971. Radiographic detection of *Agathis pumila*, a parasite of the larch casebearer. J. Econ. Entomol. 64(5):1086-1088.

Casebearer larvae, while still in their cases, were radiographed on Kodak type M film using an X-ray exposure of 5 kV and 3 mA for 4 minutes. Immature parasite larvae could not be detected consistently because their density was similar to that of the host, hence they lacked contrast. However, mature parasite larvae were detected with 100 percent accuracy. Contents of all cases were identified with up to 97 percent accuracy. Radiography may be useful where a quick check is needed to determine if the parasite is established.

2. ANDREWS, R. J. 1966. First record of the larch casebearer on western larch in British Columbia. Can. Dep. For., Bi-mon. Res. Notes 22(6):3.

Larch casebearer was first collected in British Columbia in 1966. The largest populations, averaging 4 larvae per 12-inch branch, were in the Creston area.

3. ANDREWS, R. J., and N. J. GEISTLINGER. 1969. Parasites of the larch casebearer, *Coleophora laricella* (Hbn.), in British Columbia (Lepidoptera: Coleophoridae). J. Entomol. Soc. B.C. 66:50-51.

Nine species of parasites were recovered from rearings of the casebearer in British Columbia, 1966-1968: *Bracon* sp., *Scambus decorus*, *Scambus transgressus*, *Gelis tenellus*, *Dicladocerus westwoodii*, *Tetrastichus xanthops*, *Amblymerus* sp., *Sceptrothelys deione*, and *Spilochalcis albifrons*. In 1968, parasitism averaged 4 percent, with the highest percentage (14 percent) occurring near Creston.

4. BAIRD, A. B. 1923. Some notes on the natural control of the larch sawfly and larch case bearer in New Brunswick in 1922. Acadian Entomol. Soc. Proc., N.S. (1922) 8:158-171.

Predation by five species of birds is credited with causing 25 percent mortality of casebearers in the spring. Four species of parasites were recovered, with a maximum of 8.5 percent parasitism. Nonhatch of eggs accounted for 25 percent mortality.

5. BAKER, WHITEFORD L. 1972. Eastern forest insects. U.S. Dep. Agric. Misc. Publ. 1175, 642 p.

Includes a brief description of life stages and life history of the larch casebearer in eastern United States.

6. BODEN, FRANZ. 1902. Die Lärche und die Motte. (The larch and the moth.) Z. f. Forst- u. Jagdwes. 34:21-24.

Describes the feeding behavior of the casebearer on several larch species in Germany.

7. BOUSFIELD, W. E., and R. C. LOOD. 1973. Parasites of the larch casebearer in Montana, Idaho, and Washington. Environ. Entomol. 2(2):212-213.

Twenty parasitic species were reared from the casebearer from 95 locations in Montana, Idaho, and Washington. *Spilochalcis albifrons* and *Dicladocerus* sp. were the most abundant native species recovered. *Agathis pumila*, an introduced parasite, was recovered from 58 percent of the release sites sampled.

8. BRITTON, W. E. 1924. The larch leaf-miner or case-bearer. *Coleophora laricella* Hubn. *In* 23rd Rep. State Entomol. Conn., 1923, p. 288-291. Conn. Agric. Ex Stn. Bull. 256.

Describes the larch casebearer's injury to larch, its life history, and its life stage with mention of natural enemies and control measures.

9. BRITTON, W. E. 1933. Larch case bearer, *Coleophora laricella*. *In* Plant Pest Handbook, p. 122. Conn. Agric. Exp. Stn. Bull. 344.

Briefly recounts the life history of larch casebearer in Connecticut.

10. BROWN, MARK WENDELL. 1977. A partial life table for the larch casebearer *Coleophora laricella* (LEPIDOPTERA: COLEOPHORIDAE), with notes on egg dispersion. M.S. (For.) Thesis, Univ. Idaho, Moscow, 32 p.

More than twice as many eggs were found on branches exposed to insolation as on shaded branches. A Chi-square test, the coefficient of dispersion, and Morisita's Index all showed a high degree of egg aggregation. The dispersion pattern of the eggs fitted the negative binomial distribution. Aggregation was attributed primarily to environmental conditions. Mortality during the time from oviposition to the overwintering stage was 67.68 percent. Most of the mortality was caused by density-independent factors, particularly the needle cast fungus *Meria laricis*. Egg predation and the number of nonviable eggs were significantly greater on branches exposed to insolation.

11. BURST, ROLF, and GUSTAV EWALD. 1955. Neue Untersuchungen über die Biologie und die Bekämpfungsmöglichkeiten der Lärchenminiermotte. (New investigations on the bionomics and possibilities of control of the larch casebearer.) Allg. Forstz. 10:326-329.

In an insecticide test against overwintered larvae, a spray containing 0.909 percent DNC (dinitro-orthocresol) applied on March 16 before bud burst gave 99.6 percent kill, compared with 29 percent mortality on unsprayed trees. In similar tests against activ larvae, a 0.2 percent BHC (benzene hexachloride) emulsion applied on March 31 gave 89 percent kill, compared with 9 percent for no treatment. A spray of 0.2 percent BHC or 0.3 percent malathion gave good control of the casebearer adult when applied on June 8. A spray of 1 percent DNC was applied on October 12 to induce premature defoli tion of trees while the larvae were still feeding. The needles fell within 2 weeks an examination showed that there were no larvae left on the trees.

12. CIESLA, W. M., and W. E. BOUSFIELD. 1974. Forecasting potential defoliation by larch casebearer in the northern Rocky Mountains. J. Econ. Entomol. 67(1): 47-51.

A quadratic regression model ($Y = 4.015 + 0.4419X - 0.001036X^2$) for forecasting defoliation potential by larch casebearer on western larch was developed. The model utilize systematic counts (X) of overwintering casebearer larvae on 40 branch samples per sample point to forecast the intensity of feeding injury, which is expressed as a numerical rating (Y) and can be translated into four broad classes of damage: negligible, light, moderate, and heavy. The model predicts potential feeding injury to within one defoliation class, 98 out of 100 times.

13. CODY, JACK B. 1963. The rate of spread of *Agathis pumila* (Ratz.) and its interaction with *Epilampsis laricinellae* (Ratz.). M.For. Thesis, Univ. Mich., Ann Arbor, 31 p.

Larch casebearer collections in 1954 and 1963 suggest *A. pumila* is able to spread at a rate of more than 30 miles (48 km) per year. It spread from Elmwood, Michigan, to Fosston, Minnesota, a distance of 335 miles (571 km) in 10 years. It is suggested that when both *Agathis* and *Epilampsis* are present and the casebearer population is high, the latter is the most numerous parasite. Conversely, when casebearer populations are low, *Agathis* is more numerous and *Epilampsis* is virtually absent.

14. CODY, JACK B., FRED B. KNIGHT, and SAMUEL A. GRAHAM. 1967. The hymenopterous parasites *Agathis pumila* (Braconidae) and *Epilampsis laricinellae* (Eulophidae) on the larch casebearer (Lepidoptera: Coleophoridae) in the northern Lake States. Mich. Entomol. 1(5):159-167.

Gives the history of larch casebearer and its two most important parasites in Michigan, Wisconsin, and Minnesota. Interactions of the parasites are discussed. It appears that *A. pumila* is an effective parasite by itself, but *E. laricinellae* depends upon the presence of *A. pumila* to increase its numbers to effective levels. It is suggested that alternating high populations of *A. pumila* and *E. laricinellae* result from the interactions between these two parasites.

15. COPPEL, HARRY C., and ROY D. SHENEFELT. 1960. Parasites introduced to help control the European larch casebearer--a progress report. Univ. Wisc. For. Res. Notes 53, 3 p.

Few insect parasites of larch casebearer were present in Wisconsin before the introduction of *Agathis pumila* and *Chrysocharis laricinellae*. Within 5 years both species became established, but *A. pumila* had a wider distribution and in some counties it appears to be the only beneficial parasite operative.

16. COPPEL, HARRY C., and NORMAN F. SLOAN. 1971. Avian predation, an important adjunct in suppression of larch casebearer and introduced pine sawfly populations in Wisconsin forests. Tall Timber Conf. Ecol., Anim. Contr. Habitat Manage. Proc. 2D:259-272.

Selected studies on the impact of bird predation on forest insects in different geographical regions are reviewed. Results obtained in Wisconsin in studies to determine the effects of bird predation on the larch casebearer are outlined.

17. DAVIAULT, LIONEL. 1949. Notes sur la biologie et les parasites du porte-case du mélèze (*Coleophora laricella* Hbn.) dans la province de Québec. (Notes on the biology and the parasites of the larch casebearer in the province of Quebec.) Ann. de l'ACFAS 15:90-92.

Gives the life history and biology of the casebearer in Quebec. Ten parasite species were recovered; however, the amount of parasitism did not exceed 20 percent.

18. DAWSON, A. F. 1971. Larch casebearer in British Columbia. Can. For. Serv., Pac. For. Res. Cent. Pest Leafl. 34, 3 p. Victoria, B.C.

Recounts the appearance of larch casebearer in British Columbia, including its description, its life history, the appearance of damage, and natural controls.

19. DENTON, ROBERT E. 1958. The larch casebearer in Idaho--a new defoliator record for western forests. USDA For. Serv., Intermt. For. and Range Exp. Stn. Res. Note 51, 6 p. Ogden, Utah.

Reports the discovery of larch casebearer in western larch forests around St. Maries, Idaho, in 1957.

20. DENTON, ROBERT E. 1965. Larch casebearer in western larch forests. USDA For. Serv., For. Pest Leafl. 96, 6 p. Washington, D.C.

Summarizes the casebearer's geographic range in the West, and describes life stages, life history, damage caused, and control. (Superseded by Denton and Tunnock 1972.)

21. DENTON, ROBERT E. 1967. Low-volume application of malathion for controlling larch casebearer. Mont. Acad. Sci. Proc. 1966:26-58.

Summarizes the results of aerial spray tests against the casebearer. Technical grade malathion, at a dosage of 8 fl oz per acre (584.8 cc/ha), gave 95.6 percent control of the casebearer.

22. DENTON, ROBERT E. 1967. Biological control of the larch casebearer. 18th West. For. Insect Work Conf. Proc. 1967:67-68.

Reports the initial success of establishing *Agathis pumila* for biocontrol of the casebearer in western larch forests.

23. DENTON, ROBERT E. 1972. Establishment of *Agathis pumila* (Ratz.) for control of larch casebearer, and notes on native parasitism and predation in Idaho. USDA For. Serv. Res. Note INT-164, 6 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Describes results achieved 10 years after an attempt to biologically control the casebearer by releasing 2,360 *A. pumila* at five locations near St. Maries, Idaho. Information is provided on the role of native parasites and predators as biocontrol agents.

24. DENTON, ROBERT E., and SCOTT TUNNOCK. 1968. Low-volume application of malathion by helicopter for controlling larch casebearer. J. Econ. Entomol. 61(2): 582-583.

Low-volume application of 8 fl oz technical grade malathion per acre (584.8 cc/ha) resulted in 95.6 percent control of larch casebearer.

25. DENTON, ROBERT E., and SCOTT TUNNOCK. 1972. Larch casebearer in western larch forests. USDA For. Serv., For. Pest Leafl. 96 (rev.), 8 p. Washington, D.C.

Summarizes the casebearer's geographic range in the West, its life history, damage it causes, its life stages, and natural and applied control measures.

26. DOWDEN, PHILIP B. 1934. Recently introduced parasites of three important forest insects. Ann. Entomol. Soc. Am. 27:601-602.

Reports the introduction of parasites of three forest insects. *Chrysocharis laricinellae*, *Angitia laricinella*, and *Bassus pumilus* from Austria were introduced for control of larch casebearer in the New England States.

27. DOWDEN, PHILIP B. 1962. Parasites and predators of forest insects liberated in the United States through 1960. USDA For. Serv., Agric. Handb. 226, 70 p. Washington, D.C.

ists five species of parasites introduced from Europe for biocontrol of larch casebearer n the United States. The location, year, and number of insects released are given.

8. DOWDEN, P. B., and P. A. BERRY. 1938. European parasites of *Rhyacionia buoliana* (Schiff.), *Coleophora laricella* Hbn. and *Phyllotoma nemorata* (Fall.). J. Econ. Entomol. 31:459-460.

wo of five hymenopterous parasites released in the East to control the casebearer were ecovered (*Bassus pumilus* and *Chrysocharis laricinellae*).

9. EIDMANN, H. H. 1958. Lärkträdsmalen (*Coleophora laricella* Hbn.). (Larch casebearer.) *In* Sven. Skogsvardfören. Tidskr., p. 399-418.

escribes the larch casebearer's occurrence, life history, habits, and damage it caused n Sweden.

0. EIDMANN, H. 1959. Om diapausen hos *Coleophora laricella* Hbn. (On the diapause of the larch casebearer.) Not. Entomol. 39:80-81.

iapause of the larch casebearer is closely associated with the rest period of *Larix* pecies. In November, 50 percent of the larch buds kept at 71.6°F (22°C) burst after 2 days and the casebearer broke hibernation after 23 days. In January, it was 9 to 0 days for both, and in March about 4 days for both. Thus, diapause of the casebearer epresents a physiological mechanism that helps the larvae survive the winter months nd begin feeding when their food is again available.

1. EIDMANN, HUBERTUS. 1961. Zur Entwicklung von *Epilampsis boops* Thoms. und *Cirrospilus pictus* Nees, zwei Parasiten der Lärchenminiermotte *Coleophora laricella* Hbn. (The development of *Epilampsis boops* Thoms. and *Cirrospilus pictus* Nees, two parasites of the larch casebearer.) Entomol. Tidskr. 82:52-59.

. *boops* and *C. pictus* are the most common hymenopterous parasites of *Coleophora aricella* in Sweden. The life history of *C. laricella* is described and laboratory bservations on the development of the parasites in the overwintering larvae are ecorded.

2. EIDMANN, H. 1962. Untersuchungen über die Entwicklung von Parasiten bei *Coleophora laricella* Hbn. mit Hilfe von Röntgenphotographie. (Investigations on the development of parasites of the larch casebearer with the help of X-ray photography.) Z. f. Angew. Entomol. 50:118-125.

nvestigations were carried out in 1960-61 to determine the best time in the spring to pply chemical treatments against the casebearer without injuring the eulophid parasites *Epilampsis boops* and *Cirrospilus pictus*. Overwintering larvae were collected tarting in mid-January and reared through the spring. Development of the parasites as followed by means of X-rays. It was concluded that chemical treatment should be pplied at or just before the casebearer resumes spring feeding, when the parasites re still in the immature stages in the host.

3. EIDMANN, HUBERTUS H. 1965. Ökologische und physiologische Studien über die Lärchenminiermotte, *Coleophora laricella* Hbn. (Ecological and physiological studies of the larch casebearer.) Stud. For. Suec. 32, 226 p.

comprehensive review of research in Sweden, covering the casebearer's distribution, orphology, life cycle and development, damage caused, control, effect of the environent (climatic factors, disease, parasites, predators, etc.) on fertility and mortality, luctuations in populations, and diapause.

34. ELLIOTT, K. R., and V. HILDAHL. 1966. First record of the larch casebearer in Manitoba. Can. Dep. For., Bi-mon. Res. Notes 22(4):3-4.

Reports the discovery of larch casebearer in the southeastern corner of Manitoba, Canada, in 1965.

35. ESCHERICH, K. 1931. Die Forstinsekten Mitteleuropas. (The forest insects of central Europe). 825 p. Verlag. Paul Parey, Berlin.

Includes a section on larch casebearer, giving its description, life history, distribution, damage caused, and types of natural control--mainly weather, birds, and parasite

36. EWALD, GUSTAV, and ROLF BURST. 1959. Untersuchungen über Lärchenblasenfuss und Lärchenminiermotte. (Some investigations on the larch thrips and the larch casebearer.) Allg. Forst- u. Jagdz. 130:173-181.

The spread of the larch thrips, *Taeniothrips laricivorum*, on the forest district of Neckargemünd, Germany, from 1954 to 1956 is described. Damage to larch is not simply correlated to the population density of *Taeniothrips*, but also depends on the weather that conditions the larch. Damage caused by the casebearer is described for the same period, and figures are given for population densities and winter mortality. A compar son of the growth in height of 45 infested trees and 45 trees that were kept free of the casebearer by spraying showed statistically significant differences. The susceptibility of larch and some protective measures are discussed.

37. FAL'KOVICH, M. I. 1964. Chekhlonoski (Lepidoptera: Coleophoridae) povrezhdayushchie listvennitsu V S.S.S.R., ikh rasprostranenie i istroricheskie svyazi s kormovymi rasteniyami. (Casebearers damaging the larch in the U.S.S.R., their distribution and historical relations to host plants.) Zool Zh. 43(6):851-858.

In the Soviet Union, larch is defoliated by three species of *Coleophora*: *C. laricella*, which infests *Larix decidua* in western and eastern Europe (including the Carpathian region), and two new species, described from adults of both sexes as *C. sibirica* and *C. dahurica*. *C. sibirica* mostly infests *L. sibirica* and occurs in European Russia and in Siberia (as far as the Baikal area). *C. dahurica* feeds on *L. dahurica* in eastern Siberia and the Soviet Far East. The divergence of these species from an original casebearer species appears to have resulted from the isolation of different larch species in the Tertiary period.

38. FELT, EPHRAIM PORTER. 1905. Insects affecting park and woodland trees. N.Y. State Mus. Mem. 8:170-171.

Reports the presence of larch casebearer in New York, its description, life history, and distribution.

39. FERNALD, H. T. 1919. Notes on the larch case bearer (*Coleophora laricella* Hbn.) Can. Entomol. 51(11):264.

Acknowledges the presence of larch casebearer in Northampton, Massachusetts, in 1919 with brief descriptions of the egg and first instar larva.

40. FLETCHER, JAMES. 1906. Insects injurious to Ontario crops in 1905. Entomol. So Ont. Annu. Rep. 36:90.

Reports the presence of larch casebearer on European larch at the Experimental Farm in Ottawa, Canada. Brief accounts are given of the insect's life history and habits.

41. FRANSEN, J. J. 1948. Bestrijding van de Larkismot (*Coleophora laricella*). (Control of the larch casebearer.) Ned. Boschb.-Tijdschr. 20:41-56.

Of several chemicals tested, only DNC (dinitro-orthocresol) was effective when applied against overwintering casebearer larvae.

42. FREEMAN, T. N. 1967. Annotated keys to some nearctic leaf-mining Lepidoptera on conifers. Can. Entomol. 99(4):419-435.

Six annotated keys describe the larval behavior of 28 species of Lepidoptera (including larch casebearer) that mine the leaves of *Picea* sp., *Abies* sp., *Tsuga canadensis*, *Larix* sp., *Juniperus* sp., and *Thuja occidentalis*.

43. FULMEK, L. 1917. Die Lärchenminiermotte. (The larch casebearer.) Natur. Leipzig 20:212-214.

Larch casebearer is one of the most serious pests affecting larch in Austria and Germany. Its life history is described.

44. GAUSS, RUDOLF. 1957. Die Lärchenminiermotte, *Coleophora laricella* Hb., ein neuer Schädling an der Douglasie? (The larch casebearer, a new pest of Douglas-fir?) Z. f. Angew. Entomol. 40:52-54.

In 1956, *C. laricella* was found infesting young Douglas-fir in Germany. Similar infestations had previously been reported in Austria and Holland. Foliage examination revealed high larval mortality, which was attributed to the unsuitability of Douglas-fir needles as a food source.

45. GAUSS, RUDOLF. 1960. Über Nahrungspflanzen-Wechsel bei Insekten. (On changes of food-plants by insects.) Z. f. Angew. Entomol. 45(3):313-316.

Reports larch casebearer feeding on Douglas-fir in northern Baden, Germany, in 1956.

46. GRAHAM, A. R. 1944. The establishment of some imported parasites of the larch casebearer, *Haplotilia laricella* Hbn., in Ontario. Entomol. Soc. Ont. Annu. Rep., 1943, 74:48-52.

Describes the casebearer's life history and reproductive potential, native parasitism, parasite introduction, recovery of imported parasites, and parasitic recolonization in Eastern Canada.

47. GRAHAM, A. R. 1949. Developments in the control of the larch casebearer, *Coleophora laricella* (Hbn.). Entomol. Soc. Ont. Annu. Rep., 1948, 79:45-50.

Reports the recolonization of *Chrysocharis laricinellae* and *Agathis pumila* in Eastern Canada and Newfoundland from 1942 to 1947. The biology, interrelationships, and rate of dispersal are given for both parasites.

48. GRAHAM, A. R. 1958. Effectiveness of two introduced parasites of the larch casebearer, *Coleophora laricella* (Hbn.) (Lepidoptera: Coleophoridae), in Ontario. Entomol. Soc. Ont. Annu. Rep., 1957, 88:37-41.

Casebearer larvae were obtained in April-May 1957, from larch in 56 localities in an area of 65,000 mi$^2$ (168,350 km$^2$) in southern Ontario. Dissection of these larvae showed that *Agathis pumila*, which had been liberated at four points in the area from 1935 to 1941, had become established throughout the region even though infestation by Coleophora was light and the larch stands discontinuous. The parasite may have reached the extreme northwest of the survey area from a release in Michigan in 1956 rather than from the releases made in Ontario. Parasitism varied from 41 percent south of latitude 43°N and 15 percent north of 46° to 67 percent between 44° and 45°. The average mortality of the casebearer from all other factors during the winter ranged from 2 percent south of 43° to 32 percent north of 46°. *A. pumila* is the most effective agent controlling *Coleophora* in Ontario south of Lake Superior. *Chrysocharis laricinellae*, introduce at the same time, was also recovered, but it needs a high host population for effective reproduction and had only spread a maximum of 42 miles (68 km) since 1934. There were indications that birds destroyed up to 21 percent of the overwintering larvae along their migration routes.

49. HAGEN, H. A. 1886. *Coleophora laricella* Hb, very injurious to *Larix europea* in Massachusetts. Can. Entomol. 18:125-126.

Reports the discovery of larch casebearer on *Larix europea* at Northampton, Massachusetts in 1886.

50. HANSEN, JAMES D. 1977. The biology and behavior of *Spilochalcis albifrons* (Hymenoptera: Chalcididae), a parasite of the larch casebearer, *Coleophora laricella* (Lepidoptera: Coleophoridae). Ph.D. Thesis, Wash. State Univ., Pullman, 124 p.

Reports the biology, distribution, morphology, artificial propagation and development, and behavioral observations of *S. albifrons*, a native parasite of the larch casebearer. The interactions among the casebearer, *S. albifrons*, and other parasites of the casebearer are discussed. The use of radiography demonstrated that parasitized casebearers could be easily distinguished from nonparasitized individuals.

51. HERRICK, GLENN W. 1911. Notes on the life-history of the larch casebearer (*Coleophora laricella.*). Ann. Entomol. Soc. Am. 4:68-70.

Reports on the life history and habits of the casebearer based on field and laboratory observations.

52. HERRICK, GLENN W. 1912. The larch case-bearer. Cornell Univ. Agric. Exp. Stn. Bull. 322, p. 37-54.

The first detailed report, based on observations made at Cornell University, of the larch casebearer's distribution, life history, habits, parasites, and control on ornamental larch trees in North America.

53. HERRICK, GLENN W. 1935. The larch case-bearer *Coleophora laricella* Hbn. *In* Insect enemies of shade trees, p. 138-140. Comstock Publ. Co., Ithaca, N.Y.

Briefly recounts the casebearer's description, life history, control, and injuries to eastern and European larch.

54. JAGSCH, ALBERT. 1973. Populationsdynamik und Parasitenkomplex der Lärchminiermotte, *Coleophora laricella* Hbn., im natürlichen Verbreitungsgebiet der Europäischen Lärche, *Larix decidua* Mill. (Population dynamics and parasite complex of the larch casebearer in the natural area of distribution of European larch.) Z. f. Angew. Entomol. 73(1):1-42.

The most important factors regulating density of *Coleophora* were the following: birds (in winter), intraspecific competition of young larvae mining in needles, insufficient synchronization between larvae and development of buds in spring, and unfavorable climatic factors. Parasitic Hymenoptera were unimportant.

55. JAHN, E., and A. SINREICH. 1960. Auftreten von Forstschädlingen in Österreich 1950-1959. (Beginning of forest damage studies in Austria 1950-1959). Anz. f. Schädlingskde 33:117-125.

Lists the outbreaks of 35 important forest insect pests, including larch casebearer, in Austria from 1950-1959.

56. JUNG, WILHELM. 1942. Beiträge zur Kenntnis der Lärchenminiermotte (*Coleophora laricella* Hbn.). (Contributions to the knowledge of the larch casebearer.) Z. f. Angew. Entomol. 29:475-517.

Detailed observations were made of *C. laricella* on *Larix kaempferi* and *L. decidua* during the course of an outbreak in Baden, Germany. The life history of the casebearer is given, and immature stages, larval excreta, and cases are described. Infestation for several years results in loss of tree growth and weakened trees that become more susceptible to diseases. In extreme cases, trees are killed by continuous infestation. Severest attacks occur on southern slopes of low hills and on the sunny sides of stands in flat country. For control, silvicultural practices that increase the resistance of the trees are recommended.

57. LEAPHART, CHARLES D., and ROBERT E. DENTON. 1961. Needle discolorations of western larch. USDA For. Serv. For. Pest Leafl. 61, 7 p. Washington, D.C.

Five causes of larch needle discoloration are discussed: normal physiological processes, fungus diseases, climatic abnormalities, noxious fumes, and insects.

58. LONG, GARRELL E. 1977. Spatial dispersion in a biological control model for larch casebearer (*Coleophora laricella*). Environ. Entomol. 6:843-852.

A parasite-host model, developed for the *Agathis pumila*-*C. laricella* interaction and extended to include reproductive and dispersal rates, predicts that *A. pumila* can control *C. laricella* over a 50 $mi^2$ (129.5 $km^2$) area within 8 years.

59. LOOS, CURT. 1891. Einige Beobachtungen über *Coleophora laricella* auf dem Schluckenauer Domänengebiete. (Some observations on larch casebearer in the Schluckenauer Domänen region.) Centralbl. ges. Forstwes. 17:375-379.

General observations are given on the life history and habits of the larch casebearer.

60. LOOS, CURT. 1892. Einige Beobachtungen über *Coleophora laricella* Hbn. auf dem Schluckenauer Domänengebiete. (Some observations on larch casebearer in the Schluckenauer Domänen region.) Centralbl. ges. Forstwes. 18:423-431.

A continuation of the observations on the larch casebearer cited above, but in more detail.

61. LUITJES, J. 1971. Lariksmot op douglas. (Larch casebearer on young Douglas-fir.) Nederlands Bosbouw Tijdschr. 43(1):21-24.

This investigation of the development of larch casebearer on young Douglas-fir planted under a 35-year-old stand of Japanese larch gives numbers of eggs and densities of larvae per 100 needles.

62. LYON, ROBERT L., and MARGARET E. MAY. 1970. Toxicity of aerosols to larch casebearer larvae. USDA For. Serv. Res. Note PSW-208, 3 p. Pac. Southwest For. and Range Exp. Stn., Berkeley, Calif.

Six aerosol insecticides were tested in the laboratory against larch casebearer larvae Their toxicity was determined by both direct contact and residual contact on filter paper. All six were highly toxic at less than 1.05 µg/cm$^2$ (the equivalent of 1.5 oz/a (105.1 g/ha)). In decreasing order of toxicity at $LD_{90}$ (lethal dosage for 90 percent mortality on direct contact) the insecticides were: Zectran, malathion, Sumithion (0.24-0.26 oz/acre (16.8-18.3 g/ha)), pyrethrins, Matacil (0.45-0.50 oz/acre (31.6-35.1 g/ha)), and Gardona (1.4 oz/acre (98.1 g/ha)). A dosage of 2 oz/acre (140.0 g/ha) is suggested for field trial of the three most toxic materials.

63. McGUGAN, B. M., and H. C. COPPEL. 1962. A review of the biological control attempts against insects and weeds in Canada. Part II: Biological control of forest insects, 1910-1958. Tech. Commun. 2, Commonw. Inst. Biol. Control Trinidad, 216 p.

Includes Canada's parasite introduction program for controlling larch casebearer.

64. McMILLIAN, W. D., and J. H. BORDEN. 1974. Evidence of a sex pheromone in the larch casebearer, *Coleophora laricella*. Environ. Entomol. 3(2):360-361.

Field experiments with baited traps in British Columbia showed evidence of a sex pheromone in the casebearer. Strong male response suggests that mass trapping or confusion control programs may be possible with the development of a synthetic pheromone.

65. MALENOTTI, E. 1924. Gli endofagi indigeni contro la *Coleophora laricella* (Conviene proprio aiutarne la diffusione?) (Indigenous endophagous parasite against the larch casebearer. Is it really advisable to encourage their diffusion?) L'Italia Agricola, p. 427-432.

During an outbreak of the larch casebearer in the province of Brescia, Italy, tests indicated that any wire gauze with a square mesh of 1, 1.33, or 1.66 mm width will permit the escape of the parasites of this moth. Permitting the parasites to escape from collected pupae, even if done at a cost equal to the estimated losses, only slightly assists the control of the casebearer because the collected pupae can only represent about 10 percent of the total number of casebearers.

66. MALENOTTI, E. 1935. Un problema di estetica montana: la coleofora del larice. (A problem of mountain beauty: the larch casebearer.) Atti Accad. Verona 13:153-158.

The decorative value of larch in Alpine resorts in Italy was impaired when an infestation by *Coleophora laricella* resulted in a gray and yellowish discoloration of the needles. Control was achieved on larches that were experimentally sprayed with a 5 percent tar distillate up to a height of about 25 to 31 ft (7.6 to 9.4 m) in January 1935.

67. MARTI, F. 1880. Die Lärchen-Miniermotte im Berner Oberland. (The larch casebearer in Berner Oberland.) Schweiz. Z. f.d. Forstwesen, p. 29-32.

Observations were made on the casebearer's behavioral habits in regard to feeding and selecting sites for overwintering. Severe winter cold did little harm to the casebearer once it began its winter diapause, but frost and rain during the spring feeding stage were harmful. Birds were important predators.

68. MASUTTI, LUIGI. 1961. I principali insetti dannosi alle conifere nelle valli de t. Torre e del t. Vegliato (Prealpi Giulie). (The principal conifer-damagin insects in the Torre and the Vegliator valleys (Giulia Foothills)). Collana "Tesi DiLaurea" 4:10-38.

A detailed account is given of the larch casebearer's life history and habits as observed in Italy.

69. MILLER, GORDON E., and THELMA FINLAYSON. 1974. Native parasites of the larch casebearer, *Coleophora laricella* (Lepidoptera: Coleophoridae), in the West Kootenay area of British Columbia. J. Entomol. Soc. B.C. 71:14-21.

Thirty-two species of parasites and hyperparasites were reared in 1973 from a total of almost 103,000 larch casebearers collected at eight locations in the West Kootenay area of British Columbia. The highest casebearer populations were found at Fruitvale and Shoreacres, with densities of 150 and 130 cases per 100 fascicles, respectively. The highest incidence of parasitism was 17.7 percent at Rossland, where the host density was just under 100 cases per 100 fascicles. The *Dicladocerus* spp. complex comprised 40.7 percent of the total parasitism and was abundant at Rossland, Arrow Creek, Christina Lake, Sheep's Creek, and Yahk; *Spilochalcis albifrons* comprised 23.6 percent of the total and was the most abundant parasite at Shoreacres, Christina Lake, and Fruitvale; and *Bracon pygmaeus* comprised 6.8 percent of the total and was the most abundant parasite at Anarchist Summit.

70. NEEDHAM, J. G., S. W. FOREST, and B. H. TOTHILL. 1928. Larch casebearer. *In* Leaf mining insects, p. 144-147. The Williams and Wilkins Co.

Recounts the larch casebearer's life history in eastern United States.

71. PATCH, EDITH M. 1906. Notes on insects; Larch case-bearer, *Coleophora laricella* Hbn. Maine Agric. Exp. Stn. Bull. 134:218-220.

Records the presence of larch casebearer over a large area of Maine and gives its life history.

72. PEIRSON, H. B. 1927. Larch casebearer. *In* Manual of forest insects. Maine For. Serv. Bull. 5, p. 76-78.

Describes the occurrence of the casebearer in Maine and recounts its life history.

73. POSTNER, M. 1963. Insektenschaden an der Larch ausserhalb ihred naturlichen Verbreitungsgebietes. (Insect damage on larch outside of its natural distribution range.) Forst-Wiss. Centralbl. 82:27-33.

Cultivation of larch (especially *Larix decidua*) outside of its natural range in the last 150-200 years has brought on many failures. Unfavorable climatic conditions and inadequate silvicultural measures followed by fungus disease and continual outbreaks of larch insects, especially the larch casebearer, *Coleophora laricella*, the larch sawflies, *Pristiphora erichsoni*, *P. wesmaeli*, *P. laricis*, and the larch thrips, *Taeniothrips laricivorus*, weakened the trees. Application of insecticides controlled the insects to some extent. The survival of larch grown outside of its natural range can only be attained by effective silvicultural measures.

74. PSCHORN-WALCHER, H. 1964. On the parasites of some injurious Lepidoptera from northern Japan. Commonw. Inst. Biol. Control Tech. Bull. 4:24-37.

A short review is given of parasite rearings conducted in northern Japan during the summer of 1961. The parasites of five forest insects, four orchard insects, and five field crop insects, all Lepidoptera, were investigated. The similarities between the parasite complexes of Lepidoptera in Japan and Europe are briefly outlined and discussed from an evolutionary point of view.

75. QUEDNAU, F. W. 1966. Notes on the life-history and morphology of *Chrysocharis laricinellae* (Ratzeburg) (Hymenoptera, Eulophidae), a parasite of the larch casebearer (Hubner). Ann. Entomol. Soc. Quebec 11(3):200-205.

The immature stages and life-history of *C. laricinellae*, when developing in *Coleophora laricella*, are described. Secondary sexual characters of the antenna are reported. Phenotypic variation in the coloration of the legs occurred as a result of different rearing temperatures.

76. QUEDNAU, F. W. 1967. Notes on mating behavior and oviposition of *Chrysocharis laricinellae* (Hymenoptera: Eulophidae), a parasite of the larch casebearer (*Coleophora laricella*). Can. Entomol. 99(3):326-331.

*C. laricinellae* mated readily in the laboratory when several individuals of both sexes were put together in a vial. The courtship dance performed by the male is described. Parasite females develop mature eggs 3 days after emergence and are apparently capable of resorbing the eggs if host casebearers are not available. Females can produce new eggs after host-feeding. Storage of eggs in the ovary for 5 months at 55°F (12.6°C) an sterility (phasic castration) of certain individuals is reported. Longevity at 75°F (23.8°C) of egg-laying females was about 1 month less than that of females that had not laid eggs because they did not contact hosts. Odor plays little or no role in the loca tion of the larch casebearer larvae by *C. laricinellae*, but chemical surface stimuli on the surface of a mine or case of *C. laricella* seem to be important in locating the host The parasite is also stimulated by vibrations of the host in its case. The ovipositior and host-feeding pattern of *C. laricinellae* is described. Host-feeding on fourth-insta larvae of the larch casebearer contributed little to host mortality.

77. QUEDNAU, F. W. 1967. Ecological observations on *Chrysocharis laricinellae* (Hymenoptera: Eulophidae), a parasite of the larch casebearer (*Coleophora laricella*). Can. Entomol. 99(6):631-641.

An account is given of host acceptance, the influence of temperature on fecundity and longevity, and the searching capacity of *C. laricinellae*, a parasite of the larch case- bearer. Fourth-instar case-bearing larvae were the preferred stages for attack. The size of the parasite progeny varied directly with the size of the host. Fecundity of progeny reared from small hosts was significantly less than that of progeny reared from large hosts. Not all parasite adults could successfully oviposit through the tough skin of the host pupa. *C. laricinellae* showed poor searching capacity. Superparasitis was common at low host densities of the casebearer and resulted either in only one para site emerging or in total parasite mortality. A sex ratio where females predominated resulted when sufficient numbers of fourth-instar larvae were presented to mated *C. laricinellae*. The temperature threshold for attacking hosts was 55°F (12.6°C), and fo development of the parasites 40°F (4.4°C). At 50°F (9.9°C) the adults lived an averag of 4 months. *C. laricinellae* is able to survive in the field without alternate hosts and at very low host densities. The parasite seems to depend on a continuing supply and a sufficient quantity of suitable instars of host species to be effective. If *Coleophora laricella* is the only available host species in the ecosystem, the biologic control value of this chalcid is rated as poor.

78. QUEDNAU, F. W. 1967. Notes on mating, oviposition, adult longevity, and incubation period of eggs of the larch casebearer, *Coleophora laricella* (Lepidopte Coleophoridae), in the laboratory. Can. Entomol. 99(4):397-401.

Mating in *C. laricella* took place 1 or 2 days after emergence and was stimulated by decreasing light intensity ranging from 3,000 to 200 fc (32,292 to 2,153 lm/m$^2$) within 2 hours. The female is pro-ovigenic, with peak oviposition during the first week. Optimum temperature for egg laying was 70° to 80°F (21° to 26.8°C), but a few eggs wer laid at 50°F (9.9°C) and 95°F (34.9°C). The average number of eggs deposited was abou

66. Average longevity of female adults was about 10 days at room temperature, but considerably longer at lower temperatures. Incubation period of the eggs was 12 days at 80° to 85°F (26.8° to 29.3°C) and 40 days at 55°F (12.6°C). Hatching of eggs did not occur above 85°F (29.3°C) or below 55°F (12.6°C).

79. QUEDNAU, F. W. 1968. Distribution and effectiveness of larch casebearer parasites in southwestern Quebec. Can. Bi-mon. Res. Notes 24(3):22-23.

Reports the distribution and effectiveness of two larch casebearer parasites, *Agathis pumila* and *Chrysocharis laricinellae*, in southwestern Quebec in 1967.

80. QUEDNAU, F. W. 1969. Laboratory propagation of the parasite *Chrysocharis laricinellae* (Hymenoptera: Eulophidae) and notes on interaction with its host, *Coleophora laricella*. Can. Entomol. 101(1):100-106.

A method for mass-rearing *C. laricinellae* on larch casebearer larvae, employing a water culture system for tamarack, is described. When the initial inoculum was 15 parasite females, the yield was about 100 healthy parasites from every 300 cases.

81. QUEDNAU, F. W. 1970. Competition and co-operation between *Chrysocharis laricinellae* and *Agathis pumila* on larch casebearer in Quebec. Can. Entomol. 102(5):602-612.

*A. pumila* and *C. laricinellae* compete for their common host, the larch casebearer. *A. pumila*, in sacrificing part of its own population, prevents a "one-stage condition" and helps *C. laricinellae* build up to a point where it becomes host-regulative by massive attack. Competitive displacement of *A. pumila* by *C. laricinellae* is less frequent than expected because of the different ways in which the two parasite species spread, search for, select, and attack hosts. *A. pumila* may suffer about 50 percent loss from multiple parasitism, but apparently this does not affect its survival potential, its reproductive rate, or its ability to provide significant partial control of the larch casebearer.

82. QUEDNAU, F. W. 1970. Notes on life-history, fecundity, longevity, and attack pattern of *Agathis pumila* (Hymenoptera: Braconidae), a parasite of the larch casebearer. Can. Entomol. 102(6):736-745.

*A. pumila* is a host-specific univoltine internal parasite attacking the first- and second-instar larvae of the larch casebearer. Descriptions and illustrations of all developmental stages are given. The adults mated in the laboratory when 1-day-old females were exposed to 5-day-old males. The maximum fecundity of *A. pumila* is more than 300 eggs, and in tests at 75°F (23.8°C) the average number of eggs laid per female was 139.8. Average longevity was 22.0 days. The average number of hosts destroyed with the ovipositor was 15.2 per female. The incubation period of the parasite's egg was 7 days at 77°F (25°C). The attack pattern of *A. pumila* is described. In finding hosts the parasite was guided by chemotaxis and vibrotaxis. Honey-fed *A. pumila* females, without hosts, were kept at constant temperatures ranging from 50° to 95°F (9.9° to 34.9°C). Longevity was, on the average, highest at 60°F (15.6°C) (45.6 days) and lowest at 95°F (34.9°C) (10.6 days). Superparasitism occurs in the field and laboratory.

83. RAIGORODSKAYA, I. A. 1966. Order Lepidoptera. *In* Pests of Siberian larch, p. 228,252-253, 351. A. S. Rozhkov (ed.) Acad. Sci. USSR. Sib. Dep. East-Sib. Biol. Inst. (Transl. from Russian). U.S. Dep. Agric. TT 70-50043, 393 p. Washington, D.C.

Describes insects infesting Siberian larch, with keys to species of the various families. Gives brief description of life stages and life history of *Coleophora dahurica* and *Coleophora sibirica*, illustrated with line drawings of life stages and genetalia. Suggests that damage by *C. dahurica* in some years affects 18 to 20 percent of the needles.

84. REISSIG. 1869. Die Lerchenmotte, *Coleophora laricella* Hb., *Tin. laricinella* Bchst. (The larch casebearer.) Z. f. Forst- u. Jagdwes. 1:129-137.

This is one of the earliest accounts of the life history of the larch casebearer and the nature of the damage it caused in Germany.

85. RUSH, PETER A. 1972. The larch casebearer (*Coleophora laricella*) population (LEPIDOPTERA: COLEOPHORIDAE) and its associated parasite complex on the Newcomb tract. M.S. (For. Entomol.) Thesis, Univ. Mich., Ann Arbor, 61 p.

Studies of the larch casebearer on the Newcomb Tract of the University of Michigan Forest in 1971 indicated the casebearer population was static or slightly increasing. Host tree provenances showed varying degrees of susceptibility and resistance to the casebearer. *Agathis pumila* and *[illegible] phycidis* were the two most important parasites present.

86. RYAN, R. B. 1974. Laboratory reactivation of diapausing larch casebearer larvae following different lengths of winter exposure. USDA For. Serv. Res. Note PNW-218, 4 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

Batches of field-collected diapausing larvae were transferred to a lab with a temperature of 68°F (20°C) between November and April. The number of days that elapsed before 50 percent of the larvae reactivated decreased from 28 in November to less than 1 in May. This relationship is useful in predicting reactivation of larvae for use in a laboratory rearing program.

87. RYAN, R. B. 1974. Attainment of the overwintering instar and the casebearing habit by larch casebearer larvae at different elevations in the Blue Mountain USDA For. Serv. Res. Note PNW-228, 6 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

The percentage of larvae bearing cases increased between September 11 and October 25 from 2.6 to 93 percent on plots between 3,280- and 5,545-ft (1,000- and 1,690-m) elevation. Larvae at all elevations had reached the third (overwintering) instar by October 10. This information is useful in timing parasite release or insecticide applications. Larvae at 4,000 ft (1,219 m) advanced more rapidly than larvae at higher or lower elevations.

88. RYAN, R. B. 1975. Photoperiod effects on development of the larch casebearer, *Coleophora laricella* (Lepidoptera: Coleophoridae). Can. Entomol. 107:1305-1310.

Long-day (LD = 18 light:6 dark) and short-day (SD = 12 light:12 dark) photoperiodic treatments of various sequences and durations were applied to casebearing larvae at 68°F (20°C). Continuous development did not occur at either constant LD or SD. At LD, growth of young larvae was slow and was suspended in the late second or early third instar. At SD, young larvae developed rapidly but entered diapause in the late third instar. Pupation occurred when LD followed a period of SD. Timing and synchrony of pupation in a population were shown to be controllable by specific LD and SD sequences.

89. RYAN, R. B., W. E. BOUSFIELD, R. E. DENTON, R. L. JOHNSEY, L. F. PETTINGER, and R. F. SCHMITZ. 1975. Additional releases of larch casebearer parasites for biological control in the western United States. USDA For. Serv. Res. Note PNW-242, 7 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

Reports the release of additional *Chrysocharis laricinellae* and four new parasites, *Necremnus metalarus*, *Elachertus argissa*, *Dicladocerus* "A," and *Diadegma laricinella*, for biological control of the larch casebearer in Washington, Idaho, and Montana.

90. RYAN, R. B., W. E. BOUSFIELD, C. W. JOHANNINGMEIER, G. B. PARSONS, R. F. SCHMITZ, and L. J. THEROUX. 1977. Releases of recently imported larch casebearer parasites for biological control in the western United States, including relocations of *Agathis pumila*. USDA For. Serv. Res. Note PNW-290, 8 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

eleases of *Chrysocharis laricinellae*, *Dicladocerus westwoodii*, *Dicladocerus japonicus*, *lachertus argissa*, *Necremnus metalarus* (all, Hymenoptera: Eulophidae), and *Agathis umila* (Hymenoptera: Braconidae), for biological control of the larch casebearer in ashington, Oregon, Idaho, and Montana included some newly imported stocks and additional release locations.

1. RYAN, ROGER B., WAYNE E. BOUSFIELD, GORDON E. MILLER, and THELMA FINLAYSON. 1974. Presence of *Chrysocharis laricinellae*, a parasite of the larch casebearer in the Pacific Northwest. J. Econ. Entomol. 67(6):805.

eports the discovery of *C. laricinellae* in northern Idaho and southeastern British olumbia in 1972 and 1973, respectively.

2. RYAN, R. B., and R. E. DENTON. 1973. Initial releases of *Chrysocharis laricinellae* and *Dicladocerus westwoodii* for biological control of the larch casebearer in the western United States. USDA For. Serv. Res. Note PNW-200, 4 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

otals of 240 *C. laricinellae* and 513 *D. westwoodii* (Hymenoptera: Eulophidae) from ustria and England were released in Washington and Idaho in 1972. This was the first ttempt at establishing these parasites for biological control of the larch casebearer n western North America.

3. RYAN, R. B., and C. M. YOSHIMOTO. 1975. Laboratory crossings with different sources of the larch casebearer parasite *Chrysocharis laricinellae* (Hymenoptera: Eulophidae). Can. Entomol. 107:1301-1304.

*laricinellae* from Austria, Sweden, England, and Wisconsin, some of which may be ifferent species, were crossed. Hybrid sex ratios in this arrhenotokous oecies were similar to parental types, indicating conspecificity. English and isconsin strains tended toward darker legs and female scapes.

4. SCHAFFNER, J. V., JR. 1937. The larch case-bearer (*Coleophora laricella* Hbn.). Mass. For. and Park Assoc. Tree Pest Leafl. 12, 3 p.

iefly reports the larch casebearer's distribution, life history, injury to trees, and ontrol in the New England States.

5. SCHAFFNER, J. V., JR. 1952. Larch case-bearer (*Coleophora laricella*). Mass. For. and Park Assoc., Tree Pest Leafl. 12, 1937 (Rev.). Publ. under: Baldwin, H. I., and others, Important tree pests of the Northeast, 2nd ed., 1952, p. 17-20. Evans Printing Co., Concord, N.H.

counts information reported in Tree Pest Leaflet No. 12, 1937, with minor revisions.

6. SCHAFFNER, J. V., JR. 1959. Microlepidoptera and their parasites reared from field collections in the northeastern United States. U.S. Dep. Agric. Misc. Publ. 767, 97 p. Washington, D.C.

ists 32 species of hymenopterous parasites reared from larch casebearers from 87 llections in Maine, New Hampshire, Vermont, Massachusetts, Connecticut, New York, and w Jersey.

97. SCHELLER, H. D. 1957. Versuche zur Bekämpfung von *Coleophora laricella*. Ein Beitrag zur Wirkung von Kontaktinsektiziden auf die Kronenfauna. (Tests on the control of the larch casebearer. A contribution to the effect of conta insecticides on the crown fauna.) Anz. Schädlingsk. 30(12):203-207.

A dust containing 2 percent methyl-parathion applied in September resulted in more th 90 percent casebearer mortality. Mortality of other arthropods present in the tree crowns was noted.

98. SCHIMITSCHEK, ERWIN. 1966. Über Ursachen der Befallsbereitschaft für Nadelfres ser der Lärche in ihren natürlichen Verbreitungsgebiet. (Susceptibility to defoliating insects of larch within its natural range.) Centralbl. ges. Forstwes. 83(1):1-23.

Analyzes site factors of larch stands, mainly in Tirol, Austria, subject to attack by *Semasia diniana* and *Coleophora laricella*. Studies indicated that, as a result of a long grazing history, the soils under these stands had poor aeration, slow seepage, a frequently low microfaunal densities. Pure, open stands were more susceptible than closed or mixed stands. Susceptible trees tended to have lower sap-stream velocities

99. SCHINDLER, U. 1965. Zur Bekämpfung der Lärchenminiermotte. (The control of th larch casebearer.) Forst Holzw. 20:348-353.

Infestation by *Coleophora laricella*, which declined in northwestern Germany after reaching a peak in the mid 1950's, increased again from 1963 onward. Investigations on chemical control of the casebearer were conducted in 1963-64 with a number of chem cals. Results showed that a larval density of 1 per 5 fascicles represented a threat to the trees, but chemical control was effective and longlasting. With increasing o heavy infestation, treatment should be carried out against the young larvae in the summer or early autumn with materials having some systemic effect. In a treatment applied from the ground, a parathion dust at 18 lb per acre (20 kg/ha) gave almost c plete control and was recommended. Aerial treatment with dimethoate (as Roxion) gave good control at a rate of 0.09 gal insecticide in 6.3 gal liquid per acre (0.84 lite in 59 liters/ha). When infestation is beneath the critical level but treatment is considered necessary, chemicals should be applied against the full-fed larvae in the spring. Of the materials tested, all the phosphorus compounds gave 95 to 100 percent reduction in infestation, and diazinon or dimethoate, which are relatively mild but quick acting, were recommended.

100. SCHINDLER, ULRICH. 1968. Massenwechsel eines typischen forstlichen Dauerschä lings, der Lärchenminiermotte *Coleophora laricella*. (Population change in typical perennial forest pest, the larch casebearer.) Z. f. Angew. Entomo 61(4):380-386.

The outbreak of larch casebearer in larch cultivations in northwestern Germany laste about 12 years. High population densities occurred from 1952 to 1957, followed by a decrease until 1962. Populations began to increase again in 1964. Parasitism, most by Chalcididae, was dependent on weather and host density.

101. SCHINDLER, U. 1971. Control of forest insects by ultra-low volume spraying. Plant Prot. Organ. Bull. O. E. No. 2, p. 49-55.

Chemical control trials carried out from 1967 to 1969 against 11 forest insect pests gave good results with ultra-low volume concentrates of malathion, dimethoate, and bromophos-ethyl. Motorized knapsack sprayers were used, but a helicopter spraying w 1,500 cc/ha of malathion against larvae of *Coleophora laricella* was also made in August 1968. Both methods resulted in protecting trees from significant defoliation

102. SCHINDLER, ULRICH. 1972. Einfluss der Meisen (Paridae) auf die Populationsdichte der Lärchenminiermotte (*Coleophora laricella* Hbn.) im Kalamitätsgebiet des Emslandes. (Influence of tits on the population density of larch casebearer.) Allg. Forst- u. Jagdztg. 143(1):17-20.

An experiment providing nesting sites for tits and evaluating their influence on the population density of larch casebearer is described. Findings indicated that the tits were successful in reducing the density of larch casebearer below the threshold of economic damage.

103. SCHMIDT, WYMAN C., RAYMOND C. SHEARER, and ARTHUR L. ROE. 1976. Ecology and silviculture of western larch forests. U.S. Dep. Agric. Tech. Bull. 1520, 96 p.

Summarizes and consolidates ecological and silvicultural knowledge of western larch forests, with a section on the larch casebearer as a serious pest of western larch.

104. SCHOBER, REINHARD. 1953. Die japanische Lärche, eine biologisch-ertragskundliche Untersuchung. (The Japanese larch, a biological and productive investigation.) Schriftenreihe Forstl. Fakultät u. Mitteil. Niedersächs. Forstl. Versuchsanst. 7/8, 212 S., Frankfurt (Sauerländer).

The viewpoint, repeatedly expressed in the literature, that Japanese larch is less often ttacked by larch casebearer than European larch could not be supported by observations in Germany and Holland.

05. SCHÖNWIESE, FRITZ. 1937. Einige Beobachtungen über das Auftreten und den Parasiten-Befall der Lärchenminiermotte. (Some observations on occurrence and parasitism of the larch casebearer.) Centralbl. ges. Forstwes. 63:312-316.

From May to July the rearing of parasite species from 100 casebearers produced 43 *hrysocharis laricinellae*, 26 *Microdus pumilus*, and 6 *Pteromalus semiclavatus*. Parasites reared from material collected from 1934 to 1936 from various parts of Austria ncluded the above and, in addition, *Gelis (Pezomachus) laricellae*, *Hemiteles albipalpus* ar. *austriacus* n.sp., *H. pulchellus*, *Cirrospilus (Entedon) pictus* var. *arcuatus*, and *ecremnus leucarthros*. *Necremnus* and *Pteromalus* had not previously been reared from he casebearer.

06. SCHREMMER, FRITZ. 1959. Beobachtungen und Untersuchungen über die Insektenfauna der Lärche (*Larix decidua*) im östlichen Randgebiet ihrer natürlichen Verbreitung, mit besonderer Berücksichtigung einer Grosstadtlärche. (Observation and investigations on the insect fauna of larch on the eastern edge of its natural area of distribution, with particular reference to a city-growing larch.) Z. f. Angew. Entomol. 45(1):1-48.

rom 1954 to 1956, investigations were carried out on the arthropod fauna of larch *Larix decidua*) at four localities in Austria. The results are discussed in detail, nd the species observed, including larch casebearer, are listed in a table showing the reas in which each species occurred.

07. SCHWARZ, HANS. 1933. Neue Schädlinge der Douglasie. (New pests of the Douglas-fir.) Z. f. Pflanzenkr. und Planzenschutz 43:417-418.

arch casebearer was listed among the insects feeding on Douglas-fir near Vienna.

08. SCHWENKE, WOLFGANG. 1958. Über die Standortabhängigkeit des Massenwechsels der Lärchenminiermotte, *Coleophora laricella* Hb., und der Ahorneule, *Acronycta aceris* L. (The dependence of the mass fluctuation in the larch

casebearer, *Coleophora laricella* Hb., and in the maple noctuid, *Acronycta aceris* L., on their location.) Beitrz. z. Entomol. 8(3/4):241-290.

Results are given of an investigation concerning the population density and some of th factors controlling the density of the larch casebearer (*Coleophora laricella*) and the noctuid *Acronycta aceris* at different localities.

109. SCHWERDTFERGER, F., and G. SCHNEIDER. 1957. Über den Einfluss von Lärchenminie motte Frass auf Benadelung und Zuwachs der Lärche. (The influence of larch casebearer damage on the foliage and growth of larch trees.) Forstarchiv 28:113-117.

Half of a larch stand was treated to eliminate the casebearer, and growth comparisons were made with the untreated portion for a 3-year period. Needle growth diminished between 35 and 60 percent and diameter growth diminished between 33 and 45 percent in the untreated portion of the stand.

110. SINDELAR, JIRI, and RICHARD HOCHMUT. 1972. Variability in the occurrence of so insect pests on various provenances of European larch *Larix decidua* Mill. Silvae Genet. 21(3-4):86-93.

The degree of infestation of *Larix decidua* by *Coleophora laricella* was broken down by provenance. There was a strong negative correlation with earliness and rapidity of needle flushing. A positive correlation was indicated with regard to essential oils in needles and shoots. Infestation of the one provenance of *Larix leptolepsis* was much lower than that of all the provenances of *Larix decidua*.

111. SKUHRAVÝ, VÁCLAV. 1973. Field control of the larch case-bearer moth, *Coleophora laricella*, with a juvenoid. Acta Entomol. Bohemoslov. 70(5): 313-322.

An aqueous emulsion of the juvenoid ethyl 3, 7, 11-trimethyldodeca-2, 4-dienoate was u for control against fourth-instar larvae of *C. laricella* under field conditions on plots of 100 and 500 $m^2$. A concentration of 0.1 percent caused 96 percent mortality in the field and 87 to 98 percent mortality in laboratory rearings of material collected in the field. A 0.01 percent concentration resulted in 34 to 35 percent mortality in the field, and 40 to 60 percent mortality for material brought from the field and reared in the laboratory. Problems of utilization of the juvenoid in the control of this pest are discussed.

112. SKUHRAVÝ, VÁCLAV. 1976. The effectiveness of two juvenoids on *Coleophora laricella* (Lepidoptera) in a field experiment. Acta Entomol. Bohemoslov. 73(1):59-60.

Two juvenoid compounds, with activity similar to that of juvenile hormones effective against other lepidopterous larvae, resulted in 86 to 93 percent and 47 to 66 percent malformed casebearer pupae. Both compounds prolonged the larval stage.

113. SLOAN, NORMAN FREDERICK. 1965. Biotic factors affecting populations of the larch casebearer, *Coleophora laricella* Hbn., in Wisconsin. Ph.D. Thesis, Univ. Wisc., Madison, 193 p.

Reports a study of the bionomics of *C. laricella* and its principal parasite *Agathis pumila*. Thirteen of the 93 parasites recorded for *C. laricella* were reared from collections made in Wisconsin. Only five of these (*A. pumila*, *Bracon pygmaeus*, *Gelis tenellus*, *Habrocytus phycidis*, and *Kratochviliana laricinellae*) proved to exercise any degree of control in local areas; *A. pumila* was responsible for 60 to 70 percent of the mortality caused by parasites in two areas studied. Studies in the field and in the laboratory showed that bird predation caused a considerable drop in populations of *C. laricella* in spring and that *Parus atricapillus*, *Regulus calendula*, *Dendroica magnolia*, and *D. petechia* were the most important of the 32 bird species studied.

114. SLOAN, NORMAN F., and HARRY C. COPPEL. 1964. A technique for the laboratory observation of bird predation. Proc. North Central Br., Entomol. Soc. Am. 19:63-64.

A one-way mirror was used for laboratory observation of bird predation on the larch casebearer.

115. SLOAN, NORMAN F., and HARRY C. COPPEL. 1964. An entomology research project in the arboretum--larch casebearer. Univ. Wisc., Madison, Arbor. News 13:2-3.

Preliminary results of investigations begun in 1961 at the University of Wisconsin arboretum involving caged and uncaged larch trees indicated that a combination of bird and insect predators and insect parasites achieved the best control of the larch casebearer.

116. SLOAN, NORMAN F., and HARRY C. COPPEL. 1965. Population fluctuations of the larch casebearer, *Coleophora laricella* Hbn. in the University Arboretum, Madison, Wisconsin, 1962-1964. Univ. Wisc. For. Res. Notes 122, 3 p.

Seasonal fluctuations in casebearer populations were recorded and a model life equation was developed. In this instance, beginning with one female, there was a 35 percent population increase in one generation.

117. SLOAN, NORMAN F., and HARRY C. COPPEL. 1965. Seasonal history and parasite complex of the larch casebearer, *Coleophora laricella* Hbn. in Wisconsin. Univ. Wisc. For. Res. Notes 123, 6 p.

Of the 15 species of hymenopterous parasites reared from the casebearer in Wisconsin, only five are important: the introduced species *Agathis pumila* and *Kratochviliana aricinellae*, and the native *Bracon pygmaeus*, *Gellis tenellus*, and *Hybrocytus phycidis*.

18. SLOAN, NORMAN F., and HARRY C. COPPEL. 1965. Oviposition patterns and egg predation of the larch casebearer, *Coleophora laricella* Hbn. in Wisconsin. Univ. Wisc. For. Res. Notes 124, 4 p.

esults of three separate studies showed (1) the casebearer could not survive on conierous species other than *Larix*, (2) the majority of eggs were laid in the upper and iddle portions of larch crowns, and (3) no egg parasites were found, but predation by he mirid *Derasocoris* sp. amounted to 22 percent.

19. SLOAN, NORMAN F., and HARRY C. COPPEL. 1965. The insect parasites of the larch casebearer, *Coleophora laricella* Hübner, (Lepidoptera: Coleophoridae), in Wisconsin with keys to the adults and mature larval remains. Wisc. Acad. Sci., Arts and Lett. 54:125-146.

ifteen species of parasites of *C. laricella* have been reared in Wisconsin. Two keys ere prepared to aid in separation of adult parasites and of parasite remains left in he host case. Nine species of parasites are included in each of the keys. Brief otes on the biology of each species, and illustrations and descriptions of the finalnstar cephalic structures are given.

20. SLOAN, NORMAN F., and HARRY C. COPPEL. 1968. Ecological implications of bird predators on the larch casebearer in Wisconsin. J. Econ. Entomol. 61(4): 1067-1070.

Birds are important predators of the casebearer in Wisconsin. Population decline of the casebearer in the winter, probably attributable to birds, was 23.5 percent, of which 30 to 40 percent was calculated to consist of nonparasitized larvae. Predation by birds between April and June caused a significant loss in prey population, although many of the larvae eaten were parasitized. Apparently birds did not discriminate between parasitized and nonparasitized larvae. Feeding activity in the spring was three times that recorded in the fall, under laboratory conditions, and probably reflected the "specific feeding image" developed by the birds for the larger and more active spring larvae. The magnolia warbler, *Dendroica magnolia*; the yellow warbler, *D. petechia*; the ruby-crowned kinglet, *Regulus calendula*; and the black-capped chickadee, *Parus atricapillus*, exhibited the most frequent feeding responses to the larch casebearer. No instances of "clipped-off" cases were observed in the laboratory feeding trials or in the field. Birds swallowed both case and larva completely except for the black-capped chickadee, which in the spring removed the case from the tree, extracted the larva, and then dropped the case to the ground.

121. SWAINE, J. M. 1933. Insect activities. For. Chron. 9(4):11.

Reports severe infestations of larch casebearer from Nova Scotia and Maine to central Ontario.

122. TAKAGI, G. 1932. (New forest pest in Korea.) Chosen Sanrinkwaihô 94:42-49. (Abstr. in Jap. J. Zool. 5(2):6 (1933).)

An account is given of the distribution, morphology, life history, and natural enemies of *Coleophora laricella* on two species of larch (*Larix dahurica* var. *coreana* and *L. kaempferi*) in Korea. The injury it causes and the control measures adopted are discus

123. THALENHORST, WALTER. 1953. Zur Bekämpfung der Lärchenminiermotte. (The contro of the larch casebearer.) Holz-Zentralbl. 79(81):893-894.

Several insecticides, applied as dusts or as fog solutions, gave varying degrees of success in controlling the larch casebearer.

124. THEOBALD, FRED. V. 1904. The larch *Coleophora* or leaf miner (*Coleophora laricella*, Hubner). Gardeners' Chron. 36:181-182.

Reports the presence of the larch casebearer in Britain with a description of its life history and habits.

125. THORPE, W. H. 1933. Notes on the natural control of *Coleophora laricella*, the larch case-bearer. Bull. Entomol. Res. 24:271-291.

Reports on preliminary investigations of the parasites of *C. laricella* in Europe, wit a view to possible utilization of these parasites in Canada. Systematic and biologica notes on the more important species are given.

126. TRÄGÅRDH, IVAR. 1910. Lärkträdsmalen (*Coleophora laricella* Hübn.). (The larc casebearer). Entomol. Tidskr. 31(4):258-264.

A description is given of the casebearer's life stages, life history, and the nature its damage to larch in Sweden.

127. TRÄGÅRDH, IVAR. 1915. Försök med svavelkalkvätska mot lärkträdsmalen. (Experiments with lime-sulphur against the larch casebearer). Centralanst. för Jordbruksförsök, Flygblad 49, Stockholm, Entomol. Avd. 11, 3 p.

A lime-sulphur spray was used to control the larch casebearer in the vicinity of Stockholm. Examination showed that 13 percent of the needles were attacked on sprayed trees, while on unsprayed trees 67 percent of the needles were destroyed. The experiment was repeated the following year with the sprayed trees showing 0.24 percent of their needles attacked, while unsprayed trees had 50 to 60 percent of their needles attacked.

128. TUNNOCK, SCOTT, ROBERT E. DENTON, CLINTON E. CARLSON, and WILLIS W. JANSSEN. 1969. Larch casebearer and other factors involved with deterioration of western larch stands in northern Idaho. USDA For. Serv. Res. Pap. INT-68, 10 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

In northern Idaho, dead and dying trees were found in stands of western larch that had been defoliated severely by larch casebearer during periods ranging from 4 to 10 years. Examinations determined the extent that larch casebearer and other factors contributed to this deterioration. Beetles were found in 11 of the 72 dead or dying trees sampled. Western larch borer was collected from nine trees and scavenger beetles from the other wo. In only six trees was the borer abundant enough to be a factor in causing morality. Root rot was detected in 14 of the 72 trees and could have contributed to the death of several. Tree deterioration showed no correlation with soil series or soil fertility. This study did not confirm that larch casebearer was the sole cause of tree ortality; however, larch casebearer is definitely responsible for weakening and pre-isposing western larch stands to mortality.

129. TURNBULL, A. L., and D. A. CHANT. 1961. The practice and theory of biological control of insects in Canada. Can. J. Zool. 39:697-753.

The success or failure of each of 31 Canadian biological control projects is assessed. Past experiences in Canada are analyzed, and recommendations for future work are made. There is a discussion on the philosophy of biological control and some of the popular isconceptions regarding it. Some possible dangers of biological control are mentioned.

30. VITÉ, J. P. 1954. Die Lärchenminiermotte, zur Frage des Schadens und der Gegenmassnahmen. (The larch casebearer, the question of damage and countermeasures.) Holz-Zentralbl. 80:1065-1067.

escribes the life history of the casebearer in Germany, the damage it inflicts on larch trees, and possibilities for biological and chemical control.

31. VITÉ, J. P. 1955. Der Versuch einer gleichzeitigen Bekämpfung von Blasenfuss und Lärchenminiermotte, seine Grundlagen und Aussichten. (The attempt to control thrips and larch casebearer simultaneously: its bases and prospects.) Höfchen-Briefe 8:35-53.

escriptions are given of larch thrips and larch casebearer, the damage that each insect nflicts on larch, and methods of individual control of each insect. A 5 percent concenration of the systemic insecticide Metasystox, applied by the bandage method in early uly, gave complete control of both insects.

32. VOUTE, A. D. 1952. Aantasting van Douglas door de lariksmot (*Coleophora laricella* Hb.). (Attacks of the larch casebearer (*Coleophora laricella* Hb.) on Douglas-fir.) Ned. Boschb.-Tijdschr. 24:244.

asebearer larvae were found feeding on needles of young Douglas-fir. Information is ot given as to whether the larvae completed their development.

33. WACHTENDORF, WOLFGANG. 1955. Über die Bekämpfung der Lärchenminiermotte. (On the control of the larch casebearer.) Anz. Schädlingsk. 28:101-102.

Complete control of the casebearer was achieved using backsprayers to apply sprays of Systox and Metasystox at concentrations of 0.05 percent. Control was equally good whether spraying was done in the spring or fall.

134. WASHBURN, RICHARD I., R. LADD LIVINGSTON, and GEORGE P. MARKIN. 1977. An aeria test of orthene against the larch casebearer. USDA For. Serv. Res. Note INT-226, 6 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Orthene, a systemic insecticide, proved effective against the needle mining stage of the casebearer when applied at the rate of 1 lb orthene/gal/acre (1.2 kg/9.35 liters/ The casebearer population reduction due to the spray averaged 97.2 percent.

135. WEBB, FRANK E. 1950. Biology of the larch casebearer, *Coleophora laricella* Hübner, in New Brunswick. M.S. (For.) Thesis, Univ. Mich., Ann Arbor, 58 p

Reports the first in-depth study in North America of the casebearer's morphology, its life history and development, the damage caused, and natural control factors.

136. WEBB, F. E. 1952. The larch casebearer in the Maritime Provinces and Great La region. Can. Dep. Agric. Bi-mon. Progr. Rep. 8(1):1.

Reports the duration of larch casebearer outbreaks and some biotic control factors in the Maritime Provinces and Great Lakes region.

137. WEBB, FRANK ERNEST. 1953. An ecological study of the larch casebearer. Ph.D. Thesis, Univ. Mich., Ann Arbor, 210 p.

Results are given of the most comprehensive study made in North America of the casebearer.

138. WEBB, F. E. 1957. Sampling techniques for the overwintering stage of the larc casebearer. Can. Dep. Agric. Bi-mon. Progr. Rep. 13(4):1-2.

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139. WEBB, F. E., and R. E. DENTON. 1963. Larch casebearer, *Coleophora laricella* (Hbn.). *In* Important forest insects of mutual concern to member countries the North American Forestry Commission, p. 15-17. Compiled by Working Grou on Forest Insects and Diseases, North Am. For. Comm., F.A.O.

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140. WEBB, F. E., and R. E. DENTON. 1967. Larch casebearer, *Coleophora laricella* (Hbn.). *In* Important forest insects and diseases of mutual concern to Canad the United States and Mexico, p. 58-88. Can. Dep. For. and Rural Develop.

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141. WEBB, F. E., and F. W. QUEDNAU. 1971. *Coleophora laricella* (Hübner), larch case bearer (Lepidoptera: Coleophoridae). *In* Biological control programmes again insects and weeds in Canada, 1959-1968, p. 131-136. Tech. Comm. No. 4, Commonw. Inst. Biol. Control.

Reviews the history of the larch casebearer in North America, with sections on release and recoveries of casebearer parasites and evaluations of biological control attempts.

142. WEBER, TRUTZ. 1966. Abweichungen in der Entwicklung der Lärchenminiermotte, *Coleophora laricella* Hb. (Anomalies in the development of the larch casebearer.) Anz. Schädlingsk. 39(5):72-73.

Experiments on potted larches with larvae at different stages of development showed that, under certain conditions, larvae can pupate prematurely and adults can emerge in the autumn of the year of oviposition. It seems likely that larval diapause is induced by external factors that are not yet known.

143. WEBER, T. 1966. Lässt sich das Einbandverfahren zur Bekämpfung der Lärchenminiermotte mittels systemischer Insektizide durch einfache Stammspritzung ersetzen? (Can the bandage method of controlling the larch casebearer with systemic insecticides be replaced by stem spraying?) Der Forst- und Holzwirt 21(8):182-184.

Describes tests with various insecticides sprayed to a height of 10 ft (3 m) on Japanese larch not more than 23 ft (7 m) tall in (a) early July, just before egg hatch, and (b) late July, when leaf-mining started. One percent Metasystox applied in (b) was the only pesticide that gave good control to 23 ft (7 m). Costs and labor requirements of stem spraying were about half those of the bandage method.

144. WIACKOWSKI, STANISLAW, JOZEF CHLODY, MAREK TOMKOW, MACIEJ WITRYLAK, and ADREZEJ KOLK. 1976. Studies on entomofauna of larch, alder and birch in different environmental conditions and its ecological relationships with insect pests of more important forest tree species. For. Res. Inst. and Educ. Univ., Kielce. Warsaw, Krakow, Kielce, 142 p.

Investigations of the insect fauna of European larch and other tree species are reported. A total of 95 insect species was collected from larch, including 67 phytophagous species, 13 parasitic species, 10 predaceous species, and 5 species feeding on the plant as well as animal foods. *Agathis pumila* and *Diadegma nana* were the only parasites found to be locally effective in reducing the casebearer population.

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1979. An annotated bibliography of the larch casebearer (Coleophora laricella [Hübner]). USDA For. Serv. Gen. Tech. Rep. INT-52, 29 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

The contents of 147 published references on the larch casebearer are annotated. Citations are cross-referenced by subject as well as by author. An appendix lists 30 unpublished reports.

KEYWORDS: Larch casebearer, annotated bibliography, host tree species, host tree impacts, forest insect ecology, biological control, chemical control, parasites, parasitism, bird predation.

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# APPLICATION OF ECONOMIC TECHNIQUES TO FIRE MANAGEMENT – A STATUS REVIEW AND EVALUATION

JULIE K. GORTE AND ROSS W. GORTE

CLEMSON UNIVERSITY
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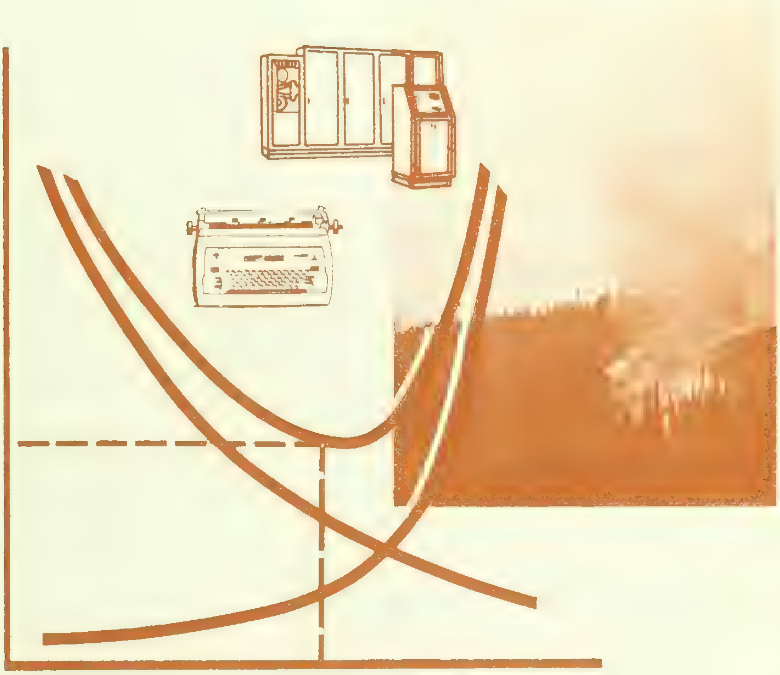

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Forest Service, U.S. Department of Agriculture

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# RESEARCH SUMMARY

The USDA Forest Service policy adopted in 1935 calls for fast, aggressive fire suppression action. Economic considerations, first voiced in 1916, quieted after 1935, until the 1960's and 1970's. The most common technique proposed is least-cost-plus-loss; the objective is to minimize the sum of all suppression and presuppression and resource losses. Another technique, benefit/cost analysis, differs only slightly. The benefits of fire control are the values protected less the resource losses; thus, least-cost-plus-loss and benefit/cost analysis will yield similar results. A third technique often proposed, the allowable burn objective, is usually not based on economic criteria and, therefore, is not discussed in depth. For any economic technique, accurate damage appraisal is needed. Appraisals are often restricted to timber because of the intangible nature of other resources. Since 1945, several attempts at complete resource damage appraisal systems have been attempted, but few have been widely applied due to the complexity of such systems.

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# APPLICATION OF ECONOMIC TECHNIQUES TO FIRE MANAGEMENT –
## A STATUS REVIEW AND EVALUATION

**Julie K. Gorte and Ross W. Gorte**

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
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# INTRODUCTION

Anyone who has searched for literature pertaining to fire economics will have realized a fundamental problem: a field of "fire economics" does not exist. Fire economics is not a special discipline like silviculture or entomology, but forest or agricultural economics applied to fire protection or fire management[1] on a limited basis.

In general, economics is concerned with the allocation of limited resources or inputs to the accomplishment of unlimited goals. It follows that fire economics is concerned with determining the share of resources to be allocated to fire management and how this share should be distributed among various fire management activities. It is assumed that fire management contributes to meeting land management objectives[2]; only in this light is fire economics of value. The Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 requires that forest resource planning integrate all its various programs, which in turn involves fire management, including both fire exclusion and prescribed burning.[3] Hughes (1976) highlights the RPA's intent with respect to the planning function:

> ". . . there was an apparent need for a Forest Service-wide planning process which encompassed all programs and which required explicit evaluation of program alternatives related to equally explicit goals. There are and have been various planning processes in all Forest Service program areas. Some are the result of technical requirements; some are the result of a wide variety of minor legislative and administrative requirements; some are linked to interagency planning activities; and some are related apparently only to the practical exigencies of preparing annual justification statements in the budget process. What has been absent, however, is an overall planning framework for relating the parts to the whole. The RPA provides this heretofore missing framework for all Forest Service planning."

To integrate fire planning in natural resource management planning, we must first ecognize the relationships of fire management to the commodities and services the orest provides. One obvious forest product is wood fiber. In addition, some forests ave aesthetic value, provide recreational opportunities, forage for domestic stock, nd habitat for wildlife, and influence the quality and quantity of water available for uman consumption, irrigation, and industrial needs. Fire management is a support function; it may either help or hinder efforts to provide forest commodities; thus, the "product" of fire management is measured in units like board feet, AUM's, or simply acres. ire planning, ideally, facilitates meeting these output-oriented goals. Economics is he rationing function, allocating resources among all competing management activities, ncluding fire management, for a maximum return within legal and policy constraints.

Inquiry into the economics of fire control and fire use has been limited because ire control organizations, while having to compete for some of their money, have also been funded substantially on a "blank check" by Forest Fire Fighting (FFF) funds. Because the funds are allocated after expenditures for suppression, some presuppressio and a limited amount of rehabilitation costs, competition for funds was of less conc in fire planning than for other forms of management. The attitudes behind this kind funding have been changing, as illustrated by the change from Protection and Mainten (P&M) funds with FFF funds to the new Fire Management (FM) funds. Fire is beginning to be seen as a process that has desirable or undesirable effects in terms of land-u goals and service and commodity flows. This idea is replacing the view that fire co trol objectives can be determined independent of land-use goals and service and comm ity flows. Consequently, economics has become a more important factor in evaluating fire management planning and policy.

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[1] Fire management being used in this paper to mean "the integrating of fire-related iological, ecological, physical, and technological information into land management to et desired objectives" (Barney 1975).

[2] Charles F. Roberts. 1976. Some considerations for fire and land use planning. meo.

[3] "Prescribed fire" will be used herein to mean any fire that is allowed to burn, gardless of the means of ignition.

This report is divided into three sections. The first section examines the rol of economic thought in the formation and development of USDA Forest Service fire poli The second section discusses the development and application of economic guidelines f investment in fire management activities. Much of section two is concerned with economic models for optimizing expenditure on fire management or for examining the cost effectiveness of such expenditure. The third section discusses the considerations necessary and the methods developed for the economic appraisal of fire effects, both destructive and beneficial. This section is limited to fire damage appraisals, and therefore does not include literature on the methods of valuing resources for purpose other than fire damage appraisal. A partial listing of works that deal with resource valuation not specific to damage appraisal is included in the appendix.

# ECONOMICS AND THE DEVELOPMENT OF FIRE POLICY IN THE FOREST SERVICE

The USDA Forest Service was formed by the Transfer Act of 1905[4] with, initially, no definitive fire policy. There was, however, concern that something needed to be done about destructive conflagrations, such as the Miramichi and Maine fires in 1825, the Peshtigo in 1871, the Michigan in 1881, and the Wisconsin in 1894, the smallest o which was one million acres (Brown and Davis 1973). The issue of conflagrations was brought up repeatedly in the ensuing decades. Loveridge (1944) attributed much of th need for development of fire policy to dry weather cycles that aggravated the fire occurrence and spread problems and led to greater resource losses. He was primarily concerned about damage, but a great deal was also written during the twenties and thi ties that dealt with how much protection was justified. Headley (1916), Sparhawk (1925), and Flint (1924; 1928) were the first to express these concerns in terms of economic or financial constraints. Much of the foundation for economic analysis of fire control was laid by these three writers, and by Hornby (1936) and Gisborne (1939 who continued the theme.

The so-called 10:00 a.m. policy was born in a meeting of Regional Foresters in 1935, following two severe fire seasons in the Pacific Northwest that killed several firefighters and destroyed timber on more than a half-million acres. Strong reactions to these and other disastrous fires prompted approval of a no-nonsense policy for the National Forests (Baker n.d.):

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[4] Transfer Act of February 1, 1905; 33 Stat. 628, 16 USC 472, 524, 554. The Organ Act of 1897 allowed for the establishment of National Forests, but not for their admin istration. The Transfer Act moved the National Forests from the Department of the Interior to the Department of Agriculture as well as providing for the administration of the National Forests.

> "The approved protection policy on the National Forests calls for fast, energetic, and thorough suppression of all fires in all locations, during possibly dangerous fire weather.
>
> "When immediate control is not thus attained, the policy then calls for prompt calculating of the problems of the existing situation and probabilities of spread, and organizing to control every such fire within the first work period. Failing in this effort, the attack each succeeding day will be planned and executed with the aim, without reservation, of obtaining control before ten o'clock of the next morning."

The 10:00 a.m. policy implies that wildfire protection is worth whatever it costs r that the values protected[5] are almost immeasurably large. At the time, this assump- ion was not unreasonable. Loss of life from wildfire was a serious threat; the Peshtigo ire alone killed 1,500 people. Loss of resources from large conflagrations, particu- arly in timber, also was viewed as critical. Thus many of the writers voicing their pinions accepted the policy as economically sound. Hornby, writing in 1936, said:

> "Attention is directed to the fact that no conflict exists between the three major objectives of fire control that have been widely recognized. Consequently, for planning purposes, the following composite objective was used. By attempting to 'Control every fire in the first work period,' it is hoped to keep burned acreage within the 'Permissable-percentage-of-burned-area,' and ultimately to make the sum of fire-control costs and losses most 'economical'."

The 10:00 a.m. policy silenced those who sought new rules for allocating funds to ire control. Primary emphasis was on efficient fire-control organizations, reducing urned acreage, and fire prevention. With the exception of Craig and others (1945; 946a; 1946b) and Arnold (1949), few people in American forestry expressed concern th economically justifiable levels of protection and control until the mid-1960's, hen Mactavish, working for the Department of Forestry of Canada, picked up essentially here Sparhawk and Flint had left off.

Alternatives to the 10:00 a.m. policy received little attention for over 30 years; e policy was evidently considered appropriate till the late sixties and seventies. the last 10 years, the policy has received a great deal of critical reexamination and e volume of economics literature in fire control (or fire management, as it has become) s expanded. The "fire economics" literature to date reveals little theoretical viation from the least-cost-plus-loss economic model proposed by Headley in 1916 and veloped by Sparhawk in 1925. These documents remain viable even on "the new frontier" fire management economics.

E. Note: Since this paper was prepared, the long-standing 10:00 am policy has been placed. Fire management policy now specifies a fire protection and use program that cost effective and is responsive to resource management goals.

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[5] For this paper, "'value protected' is the maximum potential resource value that cn be destroyed by fire on a resource management unit. This would reflect the mximum potential firecaused reduction in goal attainment." (Crosby 1977, p. 2)

# ECONOMIC GUIDELINES FOR INVESTMENT IN FIRE MANAGEMENT

Many authors have been concerned with the economically justifiable level of expenditures on fire management. Several models have been developed as economic guid lines for such determinations. The most widely discussed model is least-cost-plus-lo the level of expenditure that minimizes the sum of all costs and losses. A model tha yields similar results is benefit/cost analysis; however, this method allows comparis of fire management cost effectiveness with the cost effectiveness of other types of management. Several other models, including the allowable burn objective, are briefl discussed in the section.

## Least-Cost-Plus-Loss: Theoretical Approaches

The most widely accepted and frequently mentioned system of determining the optimal expenditures for fire management is the least-cost-plus-loss method. This method has been modified in accordance with the fire management activities that are considered critical--attack time, presuppression effort, or fire management effort. the fundamental approach is that protection level is optimized when the combined cost of prevention (including presuppression), suppression, and damage are minimized. Thes three functions are assumed to vary predictably with changing levels of presuppressio expenditure, fire management effort, or acreage burned. If presuppression expenditur is used as the independent variable input, for example, resource damage is seen as a decreasing function. In other words, as the presuppression level is increased, fire damage decreases. Suppression costs, logically, also decrease with increasing presuppression. Prevention expenditure, in this framework, is obviously as increasing function. The resulting combined function is a u-shaped curve, with the minimum point representing the optimum presuppression expenditure.

The least-cost-plus-loss approach is closely related to benefit/cost analysis, another familiar technique used to evaluate investment alternatives. The similarity lies in the concept of value protected: the two components of value protected are actual resource damages and damages averted. At any practical level of protection, some damage is sustained, while some is prevented. With no protection, theoretically, damages averted are zero, and all the values protected are lost. Benefit/cost analysi uses damages averted as its measure of benefit, to be compared to protection costs. The least-cost-plus-loss approach uses actual damages as a component of the costs to be minimized. Either method, using various presuppression levels (for an example) and measuring marginal changes, will give the same result. However, least-cost-plus-loss is used much more frequently in fire economics literature than benefit/cost because of the preceived difficulty of defining "value protected" and measuring damage averted. Given that fire has some probability of destroying or damaging resources, value protected is a viable concept. However, until this probability can be explicitly defined, the value protected (and in turn, damage averted) is not measurable. Actual damages are probably easier to assess, though this does not imply that such measuremen is simple to do.

One of the first least-cost-plus-loss models to be developed was by Sparhawk 1925). Its basic principle is to minimize the sum of "total liability" (suppression cost plus resource losses) and primary protection cost (presuppression), treating presuppression expenditure as the independent variable that determines suppression costs and damage. Sparhawk's conception of these two functions is shown in figure 1.

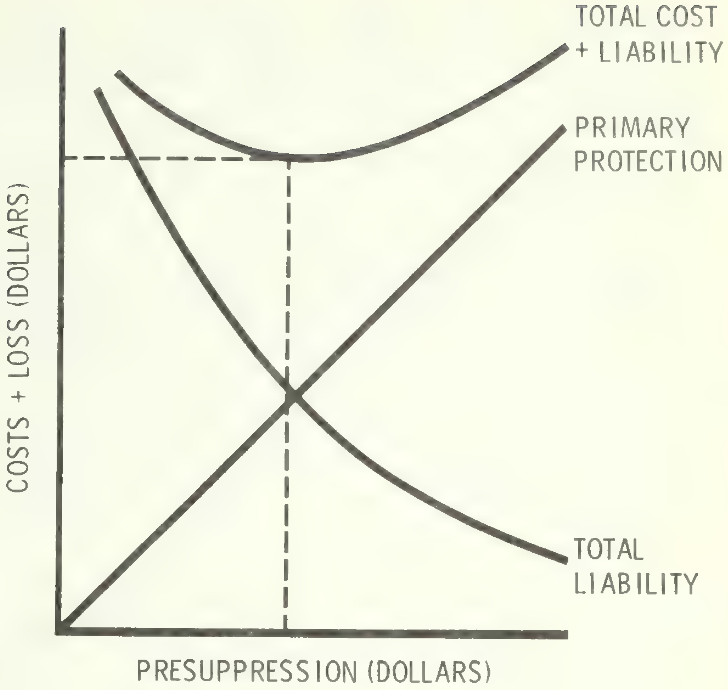


*Figure 1.--Sparhawk's total liability function.*

Total liability is, in this model, dependent on fire hazard, which in turn may be influenced by presuppression efforts that change resistance to control, manpower availability, "accessibility" (including transportation networks and detection facilities), or suppression efficiency (personnel training). An improvement in any of these parameters results in a decrease in area burned. Increases in primary protection expenditures also reduce resource losses by decreasing the expected area burned and the probable destruction if burned. Thus total liability as a whole is inversely related to primary protection efforts. The sum of primary protection and total liability is the actual cost-plus-loss function to be minimized.

Sparhawk identified timber and forage as protected values and watershed, soil, recreation, and wildlife as indirect values. In application, however, he used only the stumpage value. His reason for limiting losses to timber was "...not only because of the extreme paucity of data (for other resources), but also because the existing data indicate that such damage is less than the probable error in estimating damage to timber." No specific attention was given to the potential beneficial effects of fire.

Flint (1928) was the next to mention the least-cost-plus-loss approach. His method of arriving at the least-cost-plus-loss is essentially no different than Sparhawk's; he also makes presuppression expenditure his independent variable, though he expresses it in cents-per-acre protected instead of total spending. This is because he feels that area burned over is a more reliable indicator of fire damage than total value losses, although his reasoning is unclear. One clue might be that, in talking about losses, Flint mentions only timber value losses, "from old official records, probably not exact but believed fairly dependable." It is possible that these only ncluded stumpage values lost, though this was not specified. At any rate, Flint preferred to put expenditures and losses on a per-acre basis and minimize the total to each the objective of "adequate protection," defined as:

> ". . .that degree of protection which will render forest property as safe on the average from destruction by fire as are other forms of destructible property in which moderately conservative investors are willing to place their funds."

Flint felt that the least-cost-plus-loss solution based on "ample and dependable" data would be able to determine "adequate protection."

Hornby (1936) used a modified version of Sparhawk's approach based on using acreage burned rather than presuppression expenditure as the independent variable, as shown in figure 2. Damages and suppression costs, in this model, increase with increasing area burned. Presuppression expenditures, on the other hand, are inversel related to burned area. Hornby was convinced that the least-cost-plus-loss approach was sound but that damages were difficult to measure as a function of presuppression effort. He suggested, instead, experimenting with various levels of suppression, presuppression, and resulting damage in different time periods and using whatever combination yielded the least-cost-plus-loss figure. It was his belief that the 10:0 a.m. policy would approach this solution during critical burning periods.

Headley (1943) provides the first attempt at a thorough analysis of fire-control policy alternatives. He was concerned primarily with human values--how forest resour serve human needs--and thus regards those objectives that deal only with acreage or time constraints as unrealistic because of the lack of consistency with the changing natures of human needs and resource values. He accepts least-cost-plus-loss because does focus on human values and takes into account the fact that forests, in serving a variety of human needs, have different values over different times and areas. In oth words, least-cost-plus-loss is adaptable to changing conditions in application, while tolerable area-burned or control-time objectives are less dynamic.

Craig and others revived the model again in 1945 and 1946 in the Southern Appalachian area. Although their studies were primarily empirical and oriented towar application, their contributions to least-cost-plus-loss theory were also substantial. This group of reports is the first to attempt specific damage appraisal in terms of multiple resources and one of only a few that did more than recognized values other

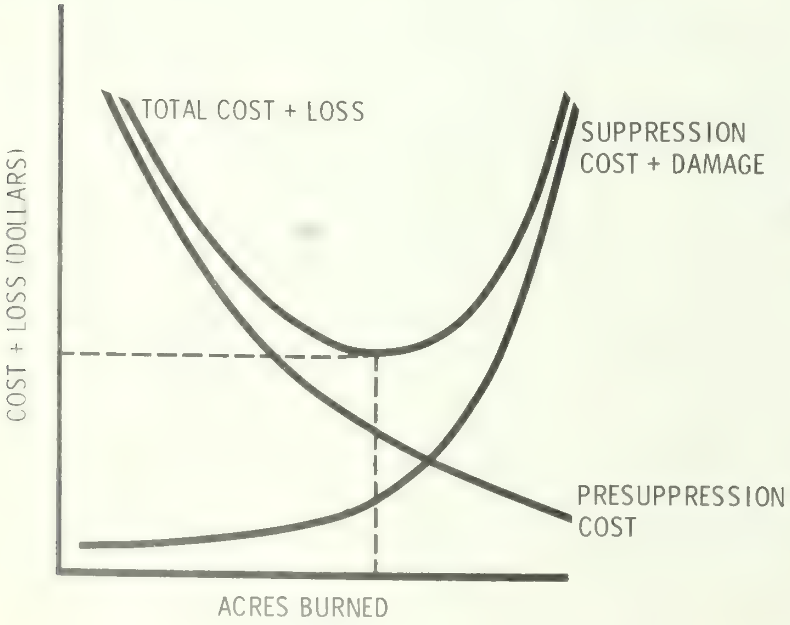


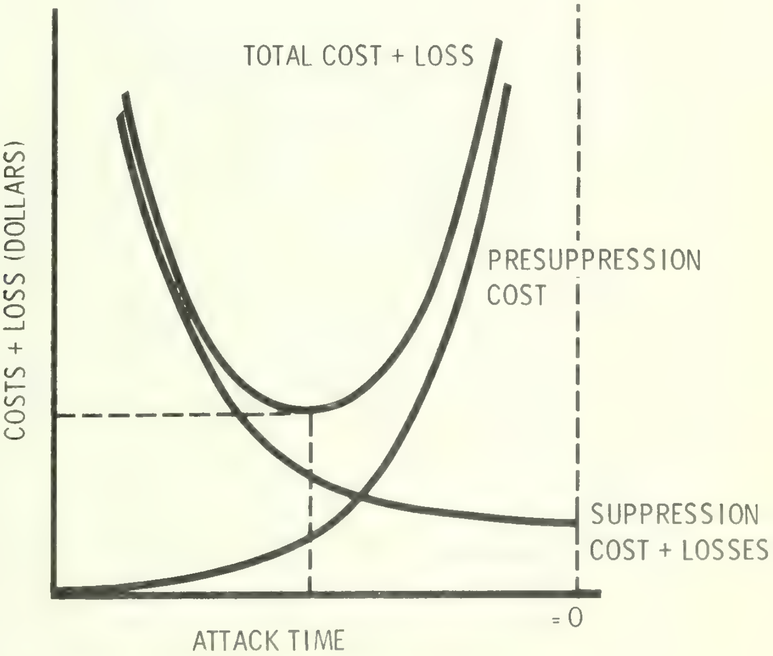
*Figure 2.--Hornby's least-cost-plus-loss model.*

than timber. Using a composite estimate of damage, then, Craig proposes comparing expenditures for suppression and presuppression with damage figures to insure that dollar increments of control (presuppression and prevention) expenditure result in at least an equivalent reduction of loss (damage and suppression). In terms of theory, Craig's major contribution is that he recognizes the need for marginal analysis; he suggests comparing several different levels of cost-plus-loss at the margin to determine a reasonable range of protection.

Arnold (1949) analyzes a number of objectives dealing with adequate fire control, and decides that least-cost-plus-loss is preferable to objectives based on allowable burned area or some measure of control time. He cites Sparhawk, Flint, and Craig as attempts to apply this method, but points out the inadequacy of their cost data and information on resource damage. He proposes a variation of least-cost-plus-loss which will minimize the problems identified. Initially, he assumes certain functional relationships among variables: suppression cost (S) depends on the number of men dispatched and the length of time fire is burning before their arrival (attack time), presuppression (P) is inversely related to attack time (which he calls hour-control or elapsed time between detection and attack), and damage (L) is a constant per acre burned. The model is built around a world of homogeneous fuels, predictable fires, and constant fire weather.

Arnold derives suppression-cost-plus-damage for a number of presuppression levels, measured by attack time. His independent variable is suppression-force size, which he optimizes for each attack time selected. He then derives total cost-plus-loss curves over a range of attack times which include presuppression costs and prevention costs as well as suppression costs and resource losses (figure 3). Prevention, which in this model is aimed at reducing fire occurrence, can be applied uniformly (a "shotgun approach") or concentrated on trouble spots. Optimal prevention levels are determined in much the same manner as optimal suppression-plus-loss figures using a percentage reduction in the number of fires as the independent variable, again over a range of attack times.

*Figure 3.--Arnold's least-cost-plus-loss model.*



Mactavish (1965) works with an expanded version of Arnold's model. In an attemp to introduce more realism, he adds in weighted averages of two stochastic variables a needed data: a frequency distribution of fire intensity and the probability of concu rent fires. He sees the suppression costs as an increasing function of crew size fo range of fire intensities, and the suppression-cost-plus-damage function as directly related to elapsed time from detection to initial attack for each intensity. Presuppression costs (detection, road building, and so on) are inversely related to elapsed time. The minimum of the sum of these two functions gives the optimum cost-plus-loss and elapsed time (attack time). While the Mactavish approach is conceptually more realistic, he suggests that various data are needed before it can be implemented in planning.

Parks (1964) also proposed the least-cost-plus-loss method as the objective of fire control organization. His efforts were directed primarily toward identifying cost relationships in fire, assuming initially that damage-per-acre is directly proportional to area burned and, therefore, that a major purpose of fire control shou be to keep all fires from blowing up. The pattern of fire growth that Parks proposed is shown in figure 4, where:

$T_I$ = ignition time
$T_D$ = detection time
$T_A$ = attack time
$T_C$ = control time
$T_M$ = mopup time
$T_F$ = final extinction time.

The most critical time elements are those of detection, attack, and control; thu the critical cost factors are identified as follows:

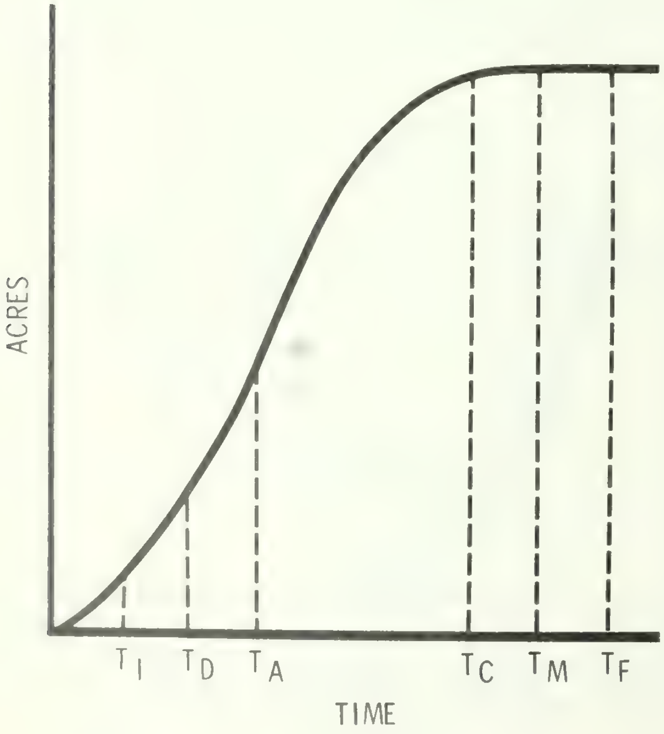


*Figure 4.--Parks' pattern of fire growth.*

1. "One-time" costs (transportation, logistics) proportional to the size of the uppression force (assumed function: linear),

2. Cost of other emergency support (communications, police, etc.) while the fire s out of control,

3. Cost in dollars per man-hour of suppression force (wages, equipment, etc.) roportional to total suppression time required,

4. Costs of maintaining fire-control organization level (assumed function: nstant), and

5. Costs of resource damage per acre (assumed function: constant at an arbitrary vel).

Because the variable costs and losses involved are, according to Parks, proportional t the size of the fire and control time, the policy implication is clearly that of eedy and energetic initial attack. Parks' model does not recognize any beneficial fects of fire and, thus, limits policy options; it does not differentiate between source damages on units with different land-use goals, and it assumes that the level presuppression is fixed.

In this sense, Parks' model is analogous to the first step of Arnold's model, in tat it examines only minimum suppression-cost-plus-loss, and does not include optimal esuppression or prevention in the solution. Gamache (1969) later extended Parks' mdel to include changes in presuppression levels and, thus, arrives at a model very smilar to Arnold's. Because Parks more or less ignores considerations other than sppression, and given his assumption that damage is a function of area burned, it is n surprise that the fire control policy implications in his paper were fully in accord wth the actual policy.

Davis (1971) compared fire protection to insect and disease control, flood control, ntional defense, and city police and fire departments in the sense that all have smilar objectives (namely, to prevent something from happening) and outputs (nonlsses). In addition, all can be treated by the least-cost-plus-loss model. Davis, hwever, recognizes some of the limitations of the model for the first time. There are tree sorts of problems: estimating costs, estimating damages, and associating changes i costs with changes in damages. Estimating costs, he says, is the easiest task, ahough care should be taken to keep data comparable over time and to record how all fnds are used. The problem of damage estimation is not so simple; Davis mentioned that mt efforts to date had considered only market commodities, and very little had been de to identify or evaluate intangible or "psychological" damages. Finally, Davis asesses the problem of associating changes in costs with changes in damages:

> "To make any comparisons at all, we need good time series data on expenditure levels and damage levels for the protected area in question. More than this, however, we need a good crystal ball. . . The big problem is that we do not really have a good way of estimating (damage with zero organized presuppression effort)."

In a memo, Boster[6] pointed out the potential inconsistency of the least-costpls-loss method with the objective of reducing area burned, both of which are program obectives of Forest Fire Prevention and Protection of National Forests. Reducing aces burned below the minimum point of the sum of damages and protection costs will case this sum to rise above its minimum dollar amount. In other words, these two objectives are mutually exclusive over some relevant range of control. In 1967, the Office of Emergency Planning, in its report to Congress, stated, "The study vividly brought to sharp focus the fact that reduction of total burned acreage, by itself, is not the full measure of effective fire control" (U.S. Dep. HEW 1967, p. 6). This inconsistency, according to Boster, is a result of the "lopsided" way in which the Forest Service has traditionally viewed resource damage, the scanty recognition given to fire benefits, and the tendency to ignore costs and concentrate on reducing burned acreage. To measure effectiveness, then, Boster suggests the objective should be to maximize the difference between damage averted and cost; stated another way, this means minimizing actual damages plus costs.

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[6] Ron S. Boster. 1976. Transmittal of fire policy report to Adrien Gilbert, pocy analysis. June 18, 1976.

Simard (1976) takes a more theoretical approach. He recognizes two faults or sources of confusion in previous works. First, there has been little consistency in defining the independent variable. Moreover, ". . .the (cost-plus-loss) diagram remains little altered regardless of how the horizontal axis is defined." Second, the relationships of cost and damage functions with their underlying production function have never been explicity examined. He develops a hypothetical production function for area burned in terms of "fire management effort" and contends that this may be translated into the traditional minimum cost-plus-loss model (in terms of eithe acres burned or fire management effort) or analyzed by marginal analysis: equating th marginal cost of "units of fire management effort" with "marginal damage" (fig. 5). Simard labels this function "marginal damage," represented by the first derivative (slope) of the production function. This is more than an extension of existing theory it is a new application of production economics. It is also consistent with micro-economic optimization techniques used for other forms of production, and in terms of economic theory it is quite sound. In addition, Simard's model is the first to treat beneficial effects of fire by the same analytical technique, thus including a greater part of the fire management picture than any other approach to date.

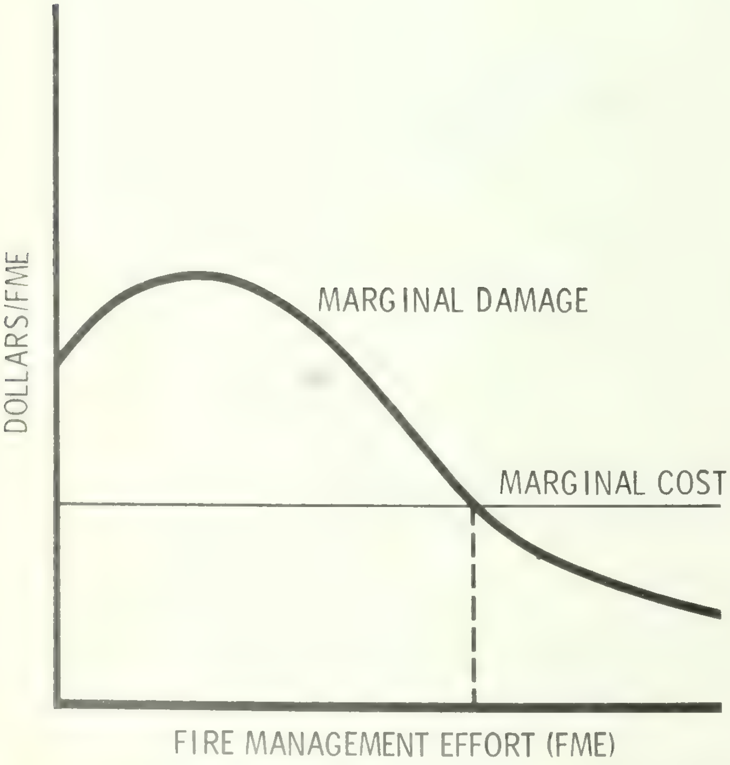

*Figure 5.--Simard's marginal analysis model.*

## Least-Cost-Plus-Loss: Applications

With the exception of Sparhawk's and Craig's work, most of the literature in the preceding sections has not dealt directly with applications of the whole least-cost-plus-loss model. Some others have picked out parts of the model and tested them with available data--notably, Parks' cost module. However, these applications were only corollaries or parts of works dealing mainly with theory, so they were included with theoretical papers rather than empirical ones.

A few workers have suggested or tried strict application of least-cost-plus-loss. Broido and others (1965) compared two actual fires in terms of cost-plus-loss, using damage to insured property as the loss figure and adding suppression expenditures.

In heavily inhabited areas, of course, the loss figure turned out to be very high, thus Broido's statement:

> ". . .an almost self-evident conclusion: spending more money (on presuppression) can greatly decrease the area burned and also the total costs of fire. . ."

is logical, given the manner in which losses are calculated, and given that suppression costs are accepted as efficient and necessary. The authors of that article suggest that it is possible to simulate damages and suppression costs using operations research techniques to determine optimum suppression levels, though they are not specific about how to do it.

North, Offensend, and Smart (1975) analyze the marginal impacts of three protection alternatives applied to the semi-urban Santa Monica Mountains:

1. Limit the number of large fires by establishing better programs for prevention and initial attack.
2. Limit the extent of large fires using fuel breaks.
3. Reduce damage by making homes more fire resistant.

The authors compute cost-plus-loss for the current system and for each of three alternatives. Only Alternative 3 offered potential for improving cost-plus-loss. Perhaps the most significant feature of this study was the use of sensitivity analysis to test the impact of changes in the large number of assumptions that needed to be made. It was found that Alternative 3 remained attractive over a range of assumptions.

Gamache (1969) takes an approach somewhat similar to Simard's in attempting to predict optimum "units of suppression" to be employed on a seasonal basis. Gamache goes beyond his predecessors in that he attempts to use his model to provide a useful management tool; i.e., he develops a predictor of the optimal level of presuppression force using a simulator. Using Parks' model of initial attack for a range of presuppression levels, historic probabilities, and expert opinion, the simulator develops fire by fire estimates of cost-plus-loss according to a given presuppression force. t probabilistically determines fires per day (concurrent fires) and aggregates these to estimate an entire fire season. By running the simulator several hundred times, for each presuppression level, a cost-plus-loss curve can be generated, and an optimal solution determined. Gamache goes on to apply his technique to a case study.

## Benefit / Cost Analysis

One of the most popular methods used to determine the financial feasibility of public and private projects is benefit/cost analysis. Briefly, benefit/cost analysis seeks to identify those projects which return some acceptable amount of satisfaction (income, flow of benefits) per unit of investment. Although, as previously discussed, this method is directly related to least-cost-plus-loss, only a few analysts have employed it because of the conceptual difficulty of measuring averted damages.

O'Connell (1971) suggested that instead of analyzing single options, all managem alternatives should be treated by benefit/cost to identify marginal benefits and cost He also cautions that all impacts (national, regional, and local) must be accounted f this applies to users of both benefit/cost and least-cost-plus-loss. The framework h suggests is a series of iterations through a linear-programming model for various management alternatives with a feedback loop to assess the impacts of management itself. Though O'Connell does not discuss fire specifically, he is interested in natural resource planning, and his results are applicable to fire control planning.

Zivnuska (1972) asserts that benefit/cost should be used to choose between prescribed burning to meet a given objective and other types of management activities, using the argument that fire management should have to meet the same benefit/cost criteria as other projects. Like many other authors, Zivnuska recognizes the problem of valuing nonmarket commodities. He stresses the need for development of better methods and prescriptions.

Jischke and Shamblin (1974) have taken a unique approach to benefit/cost analysi by integrating it with elements of least-cost-plus-loss. The cost-plus-loss figure, they assert, can be used as the benefit/cost model, though they never explained how. Their approach gives particular attention to costs and does not specify the benefits or how to measure them. This article is part of a larger treatise that includes many specific attempts at benefit/cost analysis of wildland fire presuppression and prevention.

## Allowable Burn Objectives

Many other authors who discussed allowable burn objectives are not included here because they seldom considered economic constraints. Some authors, however, have suggested that policy should be based on some kind of annual allowable burned acreage developed through economic analysis.

Beichler (1940) preferred to select the allowable-acres-burned arbitrarily, but l suggested that it could also be done by equating resource losses and costs (though th economic logic behind this method is not provided). He was convinced that the allowal burn should be based on what he called "adequate" control and that adequate control should be related to resource value. However, he offers no objective means of arrivi at either resource values or adequate control, though his feeling is that adequate co trol and "total fire exclusion" (except as a management tool) are not incompatible.

Hornby (1939) suggested using least-cost-plus-loss to develop an allowable-burn percentage of total area, though with no greater specificity than Beichler as to how to make this determination.

Gibson and others[7] take a much more innovative approach to allowable-burn determination. They suggest setting up a matrix of fire damage class and fire danger rating and determining (it is unclear as to how) an allowable-burned-acreage for each combination. These should then be compared with actual burned acreages and then revised if the actual burn is greater than the allowable. No reevaluation is suggested if the allowable burn is greater than the actual; apparently this is considered less critical. The revision, Gibson suggests, ought to take into account the productivity of the land, which resources are damaged, destroyed, or improved, and long- and short-term changes in resource outputs, tangible and intangible.

## Other Objectives

Least-cost-plus-loss, benefit/cost analysis, and allowable-burn objectives account for the vast majority of literature having to do with economic guidelines for allocating resources to fire control or fire management, but occasionally someone suggests something different.

Flint (1928) and Coyle (1929) both thought that fire damage appraisal and protection could be assessed like other property for insurance purposes. Flint wanted to spend money on protection until forest property was "as safe from destruction by fire as other forms of destructible property." Coyle suggested much the same thing; that "property in the forest should have the same call on public moneys as urban property" by units of value (not necessarily acres). Coyle was actually one of the first to be concerned with spending money on protection of forests where resource values were not sufficiently high to justify the expenditure.

Davis (1965) thought that benefit/cost analysis of alternative protection systems was good in theory, but difficult to practice because of the difficulty of measuring the benefits of fire protection. In lieu of benefit/cost, then, he suggests using protection costs and wildfire activity patterns (including average acres burned, annual variation in acres burned, and probability of specific events such as Class E fires) and that a reduction in any or all of these indicates a preferable system. He then characterized alternative management schemes as feasible or infeasible, based on the above parameters. Smith (1971) takes somewhat the same approach in suggesting that cost-effectiveness of fire protection funds needs to be evaluated.

Nautiyal and Doan (1974) propose another alternative to least-cost-plus-loss based on indifference analysis. They suggest that allowable cut and protection are interdependent determinants of the forest manager's utility (satisfaction), in that both cause a "loss of green acres." The loss of utility associated with harvested acres, however, is lessened to some degree because revenues generated can be used to offset protection expenditures. These losses of utility are translated into iso-dissatisfaction curves, each of which shows the various combinations of green acres lost and net protection cost (gross protection costs minus timber revenues) resulting in a given level of dissatisfaction. In addition, the forest manager is faced with a "protection possibilities curve" which measures the rate at which he is able to trade expenditure on protection for acres saved from burning. This rate is a function of available protection technology. The authors claim that the best protection level is that which minimizes dissatisfaction at an "adequate" level, where the protection possibilities curve is tangent to an iso-dissatisfaction curve, rather than at the minimum cost-plus-loss (fig. 6). The difference between these two levels (in monetary terms) is a measure of the manager's value of nonpecuniary commodities. This model can be extended in that the manager can further reduce dissatisfaction by increasing both

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[7] H. P. Gibson, Lance F. Hodgin, and John L. Rich. 1976. Evaluating National Forest Planning Methods and Measuring Effectiveness of Presuppression Expenditures. USDA For. Serv., East. Reg. Mimeo.

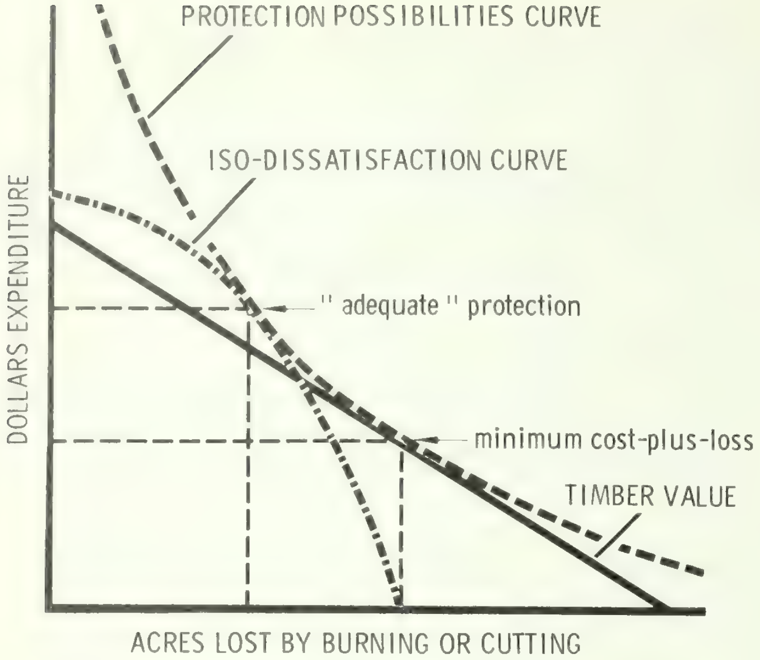

*Figure 6.--Nautiual and Doan' indifference analysis model*

protection expenditures and allowable cut. Planned cut is then increased until the lowest possible iso-dissatisfaction curve is achieved. Intuitively, the manager is trading harvested acres for burned acres and offsetting protection costs with timber sale receipts.

## Status of Economic Guidelines for Investment in Fire Management

The foregoing sections indicate that several approaches to an economically justifiable level of fire control expenditure have been developed. However, the National Forest System is not using any of these approaches. The Forest Service Manual provide that:

> "The overall objective of fire control is to provide protection to an intensity commensurate with public safety, values, hazards, risks, and management objectives involved. This includes holding fire losses (cost and damage) to a minimum. . ." (USDA For. Serv. 1972a).

This is in accord with least-cost-plus-loss methods and can also be accomplished using other methods. However, the policy that guides fire management planning is as follows

> "The basic fire control policy on National forests and National Grasslands is to provide well planned and executed fire prevention and presuppresion programs with aggressive suppression action when fires occur" (USDA For. Serv. 1970).

The policy statement is potentially in conflict with the objective; aggressive suppression may be inconsistent with minimizing the sum of cost and damages.

Ed. Note: Revision of fire management policy has brought changes in suppression polic as well. The objective of fire suppression is to control wildfire (fast, thoroughly, and safely) at reasonable cost to meet land management objectives.

The National Forest System is following the policy, with little on-the-ground emphasis on the objective. One reason for this is that fire expenditure evaluations, specifically the Monthly Fire Report (USDA For. Serv. 1973a) and the Annual Regional Fire Report (USDA For. Serv. 1973b), do not include damage totals. The reports emphasize the number and size of fires and the costs of suppression. The reports evaluate both plans and personnel accordingly. Fire planning does include damage potentials; however, from an economic viewpoint, damage forecasts are often both exaggerated and incorrect. First, estimates of damage resulting from fire typically assume that 100 percent of damage potential always results (USDA For. Serv. 1972a). This assumption provides for an overestimation of damage. The use of damage potentials is incorrect in calculating loss; "loss consists of suppression cost plus resource damage plus restoration or rehabilitation" (USDA For. Serv. 1972b, p. 43). Including both damages and restoration or rehabilitation costs double-counts the losses. Rehabilitation cost, restoration cost, or replacement cost is another measure of the resource loss.

Because of the methods used in planning and evaluation, the emphasis has been on reducing acres burned, by implementing the policy of aggressive suppression. From an economic standpoint, this system of planning and implementation may be biased; from a political standpoint, however, it may be necessary or, at least, acceptable.

The economic wisdom of aggressive fire suppression has been questioned more and more frequently in recent years. Many of the methods outlined in the preceding sections could, theoretically, provide some of the answers to questions dealing with how much should be spent on protecting forests from fire. But this is only in theory. Application of least-cost-plus-loss, or benefit/cost, or the indifference-analysis usually requires nonexistent data or the acceptance of some truly heroic assumptions, which may at least in part account for the absence of a coordinated attempt to use these models.

Some of the most doubtful of these assumptions deal with production relationships. Almost all the models begin with the argument that increased fire management results in a steadily decreasing loss, either in dollar loss or acres burned. In other words, the first step involves defining a function for relating inputs of fire management effort to reductions in losses. Such functions are never specified numerically, because the relationships are simply not known. Furthermore, there are as many of these relationships as there are combinations of fuels, weather, topography, hazard, risk, and efficiency of the fire-control effort. Zivnuska (1972) sums up the problem by saying:

> ". . .if production relationships have not been established, the economist has no basis for proceeding with an analysis and instead must fall back on two alternatives, neither of which is particularly satisfying. He may resort to the building and analysis of models of fire management. . . Alternatively, he may try himself to develop estimates of the physical production relationships, in which case he quickly moves out of the area of his specialized competence."

This statement illustrates the second major problem associated with the available economic models. As Zivnuska implies, models are built around assumed or hypothetical production functions because to specify such functions requires expertise that an economist does not possess. Even in terms of so rough a measure as acreage, production relationships are undefined, and acres are only a first approximation, anyway. To be truly representative of value, burned acres should be translated into reductions in or damage to commodities and services derived from the forest resources and from these into dollar losses. None of these functions or translations is available; and as a consequence, most of the literature is either entirely theoretical or very limited in its approach to value. Many authors, including Sparhawk and Mactavish, suggest using discounted timber stumpage values as a measure of value lost. Others recognized that many other kinds of damage could occur, but only Craig and Gamache attempted any complete quantification. Many times, too, the values used were crude or arbitrary ones because there is no procedure for deriving anything better.

Another shortcoming of most of the economic models applicable to fire control is the lack of recognition given to beneficial effects of fire. Only the models of Simard and Gamache recognize that fire could have desirable economic effects. Davis and Boste realized the problem but did not develop methods for estimation. Most of the literatur is concerned solely with fire protection and damage, rather than with net losses or net effects. As a result, most models probably overestimate the expenditure to be made on protection.

Even with all its shortcomings, economic analysis has a recognized place in fire management. At a fire policy meeting of regional foresters in July 1977 (USDA For. Serv. 1977), a significant step was taken in modifying the aggressive-suppression thinking associated with the 10:00 a.m. policy. The new suggested policy on escaped fires is "control strategy that minimizes cost plus net loss." This will not instantly solve all problems, of couse, and implementation of the new policy will require that a lot of background work be done. The available methods are not sophisticated and will not come up with perfect answers. The best that can be hoped for, at least in the near future, is planning of control strategies prior to a fire occurrence in a noncrisis situation where alternatives can be analyzed in depth.

# APPRAISAL OF FIRE EFFECTS: CONSIDERATIONS AND METHODS

Throughout the history of fire control and fire management planning and throughout the literature concerning how and why to do such planning, the problem of evaluating fire effects both physically and monetarily comes up repeatedly. Because of the scanty attention given to beneficial effects of fire and the tendency of large fires to cause obvious destruction, this whole subject area has come to be known as damage appraisal. Little has been published on damage appraisal techniques. Although many authors state that damage appraisal must account for all fire effects on all resources and that the subject deserves further research, few have attacked the problem specifically. Mitchell (1954) stated that damage estimates should be based on the "depreciated present worth" of the resource in question. Tangible and intangible items, he suggests, need to be separated; and appraisal methods need standardization. Finally, Mitchell states that sound and realistic methods for valuing intangibles are "essential."

The first attempt at damage evaluation was by Sparhawk (1925), who used stumpage loss as a measure of fire damage. He did not consider quantifying other values affected by fire. Lindenmuth and others (1951), in developing damage appraisal procedures and tables for the Northeast, stated that fires affect watershed, wildlife, soil, recreation, and other values. Owing to the lack of research, they added a $1 per acre loss onto timber losses to approximate the losses of these other resources. Craig's (1945) work was broader in scope: he attempted to evaluate damage to other forest resources as well as to timber. To assess the loss of timber value, Craig advocates using delay to future returns caused by mortality and cull, growth reduction, and stand decomposition rather than replacement cost. With respect to watershed value, Craig identifies two critical factors: (1) fire-caused damages from upland erosion, flood, and sediment, and (2) reduction of groundwater supplies. He then goes through a step-by-step process to factor out all effects on watersheds not attributable to fire and to tie the applicable effects to specific fires and quantify them in terms of value lost or injury sustained by users of water. Wildlife damage is compartmentalized into damage to animals and damage to habitat, measured in terms of dollars-per-animal figures set by the State. How the State arrived at these is not revealed. Losses to organized and dispersed recreation are measured in terms of reductions in income from fees, licenses, and the like. Other damage (forage, forest products, property, loss of life, temporary interference with lifestyles, etc.) Craig simply takes from fire wardens' reports.

In spite of all the shortcuts, Craig's appraisal remains one of the more complete reports. The next efforts were by Mactavish and Marty, both in 1965. Marty identified five ways to measure losses due to fire. The first is to use market prices, applicable only to those commodities with readily available markets. A second method is to determine replacement cost. Another way is to discount future expenses and incomes at the appropriate interest rate. The fourth method is to calculate the "conversion return"--finding a product with a market price and deducting processing costs and profits for intermediate processing. This technique would be applicable to such commodities as stumpage and forage. Marty's fifth method is to determine the opportunity cost, calculated by either the user's cost to obtain the goods or services or the income foregone by the supplier in providing them. Marty recommends this technique for nonmarket commodities. Mactavish identified only timber values lost, choosing the net present value of future harvests lost minus salvage as the best method to estimate timber damage. McLean (1970) also confines his appraisal to timber value, his primary goal being to develop a method of evaluating damage to immature timber. He, too, argues that he present net worth of the expected harvest value should be used to evaluate how much s lost when an immature stand is burned. When the stands are underutilized or overtocked, an estimated percentage of the expected stumpage value should be used instead. he damage figures are developed by subtracting the expectation value of bare land assuming all timber is lost) from the expectation value of the stand before fire.

Harrison and North[8] compiled a matrix of fire effects to be considered in damage ppraisal, though they do not attempt to value any of them specifically. Resource ategories are timber, range, soils, water, property and improvements, health and life, ildlife and recreation, smoke, and hazard from future fires. The values affected inlude owner values, user values, and externalities. The list is complete, and while n individual fire may not affect all categories, all should be considered.

The literature dealing with the least-cost-plus-loss approach usually suggests hat fire damages and effects are measurable. Almost all the authors who deal with ne subject assert that numerous problems are associated with such measurement, though ew of them attempt to deal with the problems directly. Because timber (and someimes forage) values are established by market processes, many of the writers have used hese as estimators of resource value, preferring to ignore less tangible effects. thers have suggested using acres burned to indicate resource damage. Williams (1969) ommends this alternative as "wise", due to lack of information about monetary losses, nd suggests using an operations research-linear programming approach to allocate fire ontrol money. Noste and Davis (1975) spell out why they think damage appraisal is so fficult. The problem, they assert, is complex because many of the resources proected have nonmarket values and because it is difficult to say which resources will threatened by fire and how much damage or benefit these resources may sustain as a sult of fire. They also question whether economic analysis of fire effects will tually be used in an unbiased fashion in allocating resources to fire management tivities. Historically, they maintain, money invested in fire control has not paid f; however, it should be recognized that little economic analysis has ever actually en done and applied to real-world fire problems.

Even more recently, a task force made up of USDA Forest Service planners concerned th economics in fire management planning (Chandler 1977) reiterated that fire damage appraisal is "hideously complex" due, at least in part, to the nonmarket values and the lack of critical data. There are three general data needs that the task force identified: the relationship between fire size-intensity and various kinds of suppression activities, a model of how fire size-intensity affects commodity flows, and specif relationships between physical and monetary commodity flows.

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[8] J. Michael Harrison and D. Warner North. 1972. The economic assessment of fire fects: a first look at the problem in southern California. Stanford Res. Inst. Proj. mo. 1555-3. June 14, 1972. Menlo Park, Calif.

Brown and Boster (1974), Brown and others (1974), Davis[9], and Gale (1976) all measure fire management benefits in the same terms: the benefits of fire management are values at risk (value protected) minus actual damage, where actual damage is calculated for the area both with and without fire management. Vasievich (1976) used a similar approach for evaluating the cost effectiveness of prescribed burning in the South. All of these approaches fit into the least-cost-plus-loss model in that they are concerned with movements along the cost-plus-damage function and shifts in the curve itself. Flint (1924) takes an approach similar to this in measurement of fire damages: the value of resources before fire less the value after fire is an indicator of damage.

Gisborne (1939) suggested a stepwise approach to a measure of total danger:

1. (rate of fire spread) x (dollar damage per acre) = dollar damage per hour,
2. (dollar damage per hour) + (control expenditure per hour) = dollar cost per hour,
3. (dollar cost per hour) x (fire occurrence index) = total danger.

Gisborne's "total danger" approach, applied to some management unit, simply assumes that the most unattainable piece of information (dollar damage per acre) is either available or can be developed.

In 1966, Countryman recommended a similar approach to damage appraisal. He states that damage rate is proportional to susceptibility to damage. He goes on to say that some resource damages are linearly related to fire size, such as timber and forage losses, while other damages are exponentially related. He cites a watershed study in southern California where watershed damages increased by more than 40 times when fire size increased by 20 times. However, Countryman does not propose how to identify the relationships between fire size and resource damage.

In 1975, Bakker did a very complete financial analysis of actual fire effects on a watershed in northern Washington, identifying primary and secondary effects both on the watershed and in affected local areas. Timber losses were measured by present net worth of stumpage-less-salvage value, as well as in the effect of changed harvests on the local logging industry. Water yield and sediment were the parameters used to evaluate fire effects on watershed; the value of increased water yield was measured by the value of additional power it generated and increased sale of water for irrigation. Increased sedimentation was valued by damage to all direct water uses that were affected. In addition, he included property damages caused by fire-related mudslides. Recreation values were estimated by multiplying the change in use (in visitor days) by values per visitor day developed for various kinds of recreation in a study by Dyrland in 1973. Wildlife values were evaluated in much the same manner, using the change in visitor days of hunting and fishing caused by changes in animal and fish populations due to fire. Property and improvements were evaluated by individual replacement value. Other effects (which turned out to be insignificant in this case, according to Bakker) were identified to be impacts on grazing, research, and air pollution, and on emotional, aesthetic, and educational values. Losses of life were evaluated using the statistical value of a life determined by the U.S. Department of Transportation.

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[9] Lawrence S. Davis. 1974. An exploration of the economics of fire management programs in the Rocky Mountains with emphasis on information needs. (Draft.) April 1 1974.

Bakker's analysis is one of the most complete treatises available for fire damage appraisal and is oriented more toward specific application. An analysis by Crosby (1977) is more theoretical. Both analyses are adaptable; and more important, both consider that fire effects may be beneficial as well as harmful. Crosby is most concerned that all effects be evaluated in light of land management objectives to serve human needs. He emphasizes that the critical evaluation is the "value protected," or those values that are potentially destructible by fire. This, he asserts, is less than the total resource value. Fire is incapable of "destroying acres," in the vernacular of countless fire reporters; it cannot remove acres from the face of the earth. Crosby then directs his efforts toward developing step-by-step methods for evaluating the impacts of fire on forest and wildland recreation, wildlife, property, human comfort and convenience, aesthetics, the atmosphere, water, watersheds, timber and the timber industry, and range. In some cases where values are nonpecuniary, he develops methods of ranking damage in an ordinal fashion and suggests using arbitrary value classes corresponding in magnitude to the importance of the ranking.

Brown and Boster (1977) have described an alternative to the present-net-worth-of-arvest-expected methods in valuing timber losses. The method, known as the "with and vithout" approach, had been known for a few years, but was not specifically related to fire effects. Basically, it spreads the impact of lost timber harvests over the entire anagement area in terms of the effect of future harvests and harvest values. This ethod realizes, as does the Nautiyal and Doan approach, that there is more than one anagement alternative and that the forest manager may trade alternatives against one nother to change the immediate impact. Unless the whole management area is lost, the anager may postpone or soften the immediate impact of fire by rearranging harvesting chedules on the rest of the unit for, if necessary, the entire next rotation to reduce he present value of the impact of timber lost.

## Status of Fire Effects Appraisal

Attempts at comprehensive damage appraisal are frustrated by the difficulty of lacing a value on nonpecuniary goods and services such as recreation values, wildlife alues, and aesthetic values. In most instances, the physical effects of fire on esources are not known. Even if they were, the problem of valuing them is no less ifficult. All that can be said is that wildlife, for example, has some value because eople desire it. In any context, valuation of such nonmarket amenities is difficult. ome approaches have relied on giving such amenities an ordinal ranking; Crosby uses his method. But if the valuation is being used to define dollar expenditures, a roblem still exists. This can be solved by applying arbitrary dollar amounts to ifferent rankings, in which case the value in question may or may not represent the esources' real value to society.

Timber, wood products, and forage are traded in markets and, therefore, have rket-determined values; but the problems of defining loss or benefit are still not lved. The market stumpage value for instance, is really only applicable on manage-nt units that are operated to maximize profit, which the Forest Service is legally ohibited from doing. So, because the full allowable cut is not always cut ecognizing that allowable cut is not determined on the basis of an economically timal rotation), how can timber loss be evaluated? Unless the timber is actually heduled for harvest, and assuming that there are reserves of timber which can be rvested, it is arguable as to whether the full discounted stumpage value is really st. Furthermore, discounted value itself is a rather unreliable measure of value ven the long investment periods involved in much of forestry, the difficulty in fining the "correct" discount rate, and the unreliability of prices in the short run.

Another problem associated with damage appraisal is how to treat off-site values. For example, smoke may cause people great temporary inconvenience, damage to watershed can contribute to downstream flooding and damage to water quality, highways and transportation systems may be upset, and so forth. The effects may be benefical, too; increases in water runoff due to fire may generate additional hydroelectric power. In any case, evaluation of these off-site effects is fraught with difficulty, as is any other facet of damage appraisal.

In short, damage appraisal is an inexact science, but the information yielded by an appraisal is necessary for evaluating the benefits of fire management. We find ourselves in agreement with those who suggest that more work be done on developing acceptable methods for damage appraisal.

# SUMMARY

Economics is concerned with allocating limited resources to meet unlimited goals. In fire management, the limited resources are the funds available to meet fire management objectives. Historically, these resources have not been limited, through the use of FFF funding. With this funding procedure and the 10:00 a.m. policy calling for aggressive fire suppression, it is possible to exceed protection commensurate with resource values--the objective of fire management. Concern for the economic justification of fire management expenditures was first expressed in the 1920's and 1930's. It quieted after the adoption of the 10:00 a.m. policy, until the 1960's when the concerns resurfaced. In 1977, the USDA Forest Service altered its policy to more closely conform with the objectives of fire management.

Several models have been proposed as economic guidelines for determining fire management expenditures. The most widely discussed model is least-cost-plus-loss. This model defines optimal protection as that level which minimizes the sum of prevention, presuppression, and suppression costs and resource losses. The costs and losses are generally assumed to vary predictably with presuppression expenditures, fire management effort, acres burned, or some other independent variable.

Benefit/cost analysis is another model that has been proposed. It can be used to determine the economically optimal level of funding, as with the least-cost-plus-loss model. When the benefits are calculated as the difference between values protected and actual damages, benefit/cost analysis will yield results identical to the results of least-cost-plus-loss. One advantage of benefit/cost analysis, however, is that it can be used to examine marginal expenditures; a benefit/cost analysis for a particular fire management project is comparable to similar analyses for projects in other resource areas. This is a useful advantage for determining short-run changes in fire management expenditures.

Several other models have been proposed. The allowable burn objective is common in the literature, but there is very little discussion of the economic rationale for this model. Other suggestions include protection to bring forests to an insurable level commensurate with other property, measuring wildfire activity patterns instead of resource losses, and using indifference analysis (a theoretical economic model with less applicability than benefit/cost analysis or least-cost-plus-loss).

It is difficult to apply any of the models discussed above. One problem is that all of the models assume that there is a known relationship between fire management and resource losses. In actuality, the relationship is not known; in fact, there has been some question as to the nature of the relationship. Questions arise as to the linearity of the relationship between acres burned and resource damage. It is even possible that acres burned and fire management efforts are not correlated, or at least there is no evidence of the relationship in the literature.

A second problem in applying the economic models is that all assume that resource losses are measurable. However, this measurement is given scanty attention in the literature. Often times, only timber or timber plus forage are used as resource losses. Even in timber, there is room to question the amount of loss when a tree burns; is the current market value lost if the tree was not marked for immediate sale; if not, what is the appropriate discount rate to use for future market values; what are future market values going to be? There are also problems arising in the measurement of nonmarket goods and services. Precise values are virtually impossible to determine, and it is difficult to determine values that are acceptable to all or even many of the affected parties. In addition, there is the problem of determining off-site damages; what is the loss due to soil movement, water pollution, and air pollution? This is an area that needs substantial research before progress in the field of fire economics can be made.

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# APPENDIX

## Nonfire Related Resource Valuation Models

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# RECOVERY OF SNOW-BENT YOUNG WESTERN LARCH

Wyman C. Schmidt and Jack A. Schmidt

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U.S. DEPARTMENT OF AGRICULTURE

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June 1979

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
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U.S. Department of Agriculture
Ogden, Utah 84401

# RESEARCH SUMMARY

Heavy winter snowfalls are common in the subalpine forests of the Northern Rockies. These forests are generally well adapted to winter snows. But occasionally unseasonal, heavy, wet snows damage these forests. In June 1966, a heavy,wet snow flattened many young stands in the Flathead area of northwestern Montana. Included was a 13-year-old western larch stand on one of our stand development study areas on Coram Experimental Forest. Photographic evaluations of this stand over an 11-year period following the snowfall showed that: (1) all trees in the sample, regardless of severity of the snow damage, eventually recuperated; (2) slightly snow-bent trees returned to vertical within 2 years, moderate and heavily snow-bent trees within 4 years, and severely snow-bent trees within 6 years; (3) the most apparent aftereffects were crooks in the tree boles, with the extent of crook deformities directly related to the severity of the snow bend: (4) dominant and nondominate trees recovered at about the same rate. These results illustrate phenomenal recuperative abilities of vigorous young larch and demonstrate to the manager that snow bend doesn't always reduce his management options.

# INTRODUCTION

Heavy snowfalls are common in the subalpine forests of the Northern Rockies. Favorably, snow provides much of the moisture for these forests. Unfavorably, heavy wet snow that accumulates on the crowns can damage trees extensively over large areas. In addition, movement of deep snowpacks down the steep mountainside can seriously deform trees (Leaphart and others 1972).

Snow damage is certainly not an uncommon phenomenon in conifer forests of the Northern Rockies, but its occurrence is erratic and unpredictable. Effects may range from a significant forest management problem to a mere ripple in the flow of forest succession. In some cases snow damage may help the manager--hastening the thinning of natural overstocked stands by reducing the number of trees per acre (Haig and others 1941; Blum 1966). However, this same amount of damage and mortality is not welcome in stands that have been thinned or planted--they are already near their desired stocking level.

## What is this paper about?

The results of snow damage in a young western larch (*Larix occidentalis* Nutt.) forest are reported in this paper. Larch is a deciduous conifer, losing most of its needles in October. Thus, larch is essentially bare during the winter snow period with no crown to "catch" the snow. As a result, snow is not commonly thought to be a threat to larch (Schmidt and others 1976).

Because larch is deciduous, natural selection for snow damage resistance has probably been less rigorous for larch than for some of its associate conifers. Thus, when larch has a full complement of needles, it may be less resistant to snow than other conifers.

## Why did we study snow-bend?

On June 4, 1966, forested areas in the Flathead River drainage of northwest Montana were blanketed with 6 to 8 inches (15-20 cm) of heavy, wet snow. By this date, larch needles are fully developed. One of our stand development study areas on Coram Experimental Forest was in the main path of the snowfall. Most of the sapling stands--primarily western larch--on the Forest were flattened by the weight of the snow blanket. It appeared as if the young stands were "mowed down." However, closer examination revealed that damage was not uniform within stands; some trees were horizontal, others stood at 45 degree angles and others were only slightly bent. Snow bend predominated but some trees had broken tops or split stems.

Would the snow-bent trees eventually straighten up? Would the larger dominant trees recover as well as or as rapidly as the smaller codominant and intermediate trees? Would there be any tree mortality? If they recovered, how long would it take?

## How did we study snow-bend?

To answer these questions, we devised a pictorial scheme to evaluate recovery of the trees. We selected individual trees by damage categories and crown class and photographed them from the same point over a period of 11 years--annually the first 5 seasons, and again in the 9th and 11th seasons. We chose the following categories:

*Damage classes*

| | |
|---|---|
| Slight | (averaged 15° from vertical) |
| Moderate | (averaged 31° from vertical) |
| Heavy | (averaged 56° from vertical) |
| Severe | (averaged 67° from vertical) |

*Crown Classes*

Dominant
Nondominant (mainly intermediates with some codominants)

*Replicates*

Three
This made a total of 24 trees photographed.

We took the first series of photographs June 29, 1966, about 3 weeks after the snowfall. Some of the trees had already started recovery from the snow bend so, if anything, the initial angles of snow bend are conservative. Most photos were repeated in June or July, but some were taken in the fall or spring when the trees were defoliated to better illustrate crooks and bends of the main bole.

The trees we sampled were part of a 13-year-old larch stand that had been thinned 5 years earlier. Sufficient time had elapsed since thinning for the trees to fully adjust to their current stand density and the stand was in a good healthy condition at the time of the snowfall. Stand densities around the sample trees ranged from 300 to 1,700 trees per acre (120 to 680 trees per hectare) but no attempt was made to sample by stand density. This area is a good quality site for larch, falling in the *Abies lasiocarpa/Clintonia uniflora* habitat type (Pfister and others 1977). At the time of the snow, the stand averaged about 15 feet (4.5 m) in height.

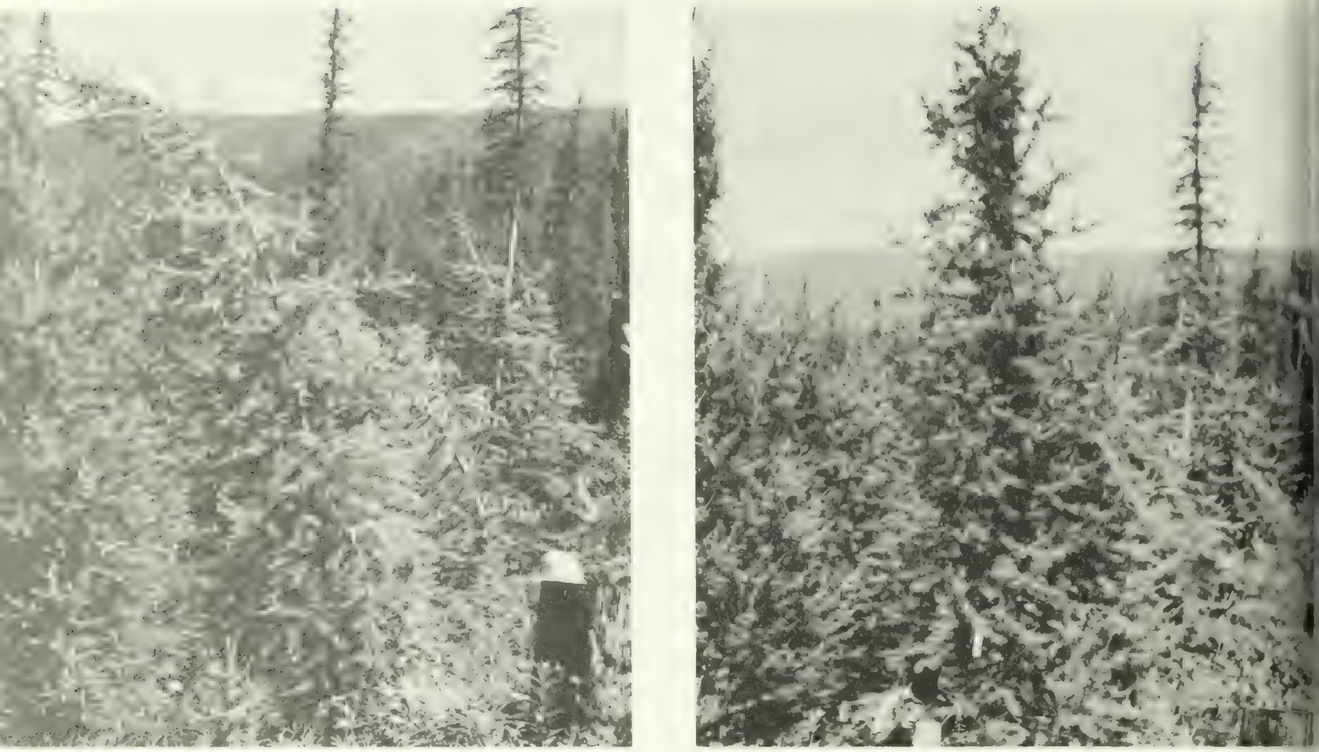
## Vhat did we earn about ;now bend?

Very simply, the slightly snow-bent trees rapidly returned to vertical with few aftereffects--the severely snow-bent trees returned slowly to vertical and suffered more aftereffects such as crooks in the bole. The basis for this is shown in both pictorial examples (fig. 1) and in schematic drawings that highlight the bole configurations (fig. 2).

To quantify the recovery rates, we measured the angle from vertical of every sample tree (fig. 3). As shown in table 1, the slightly snow-bent trees returned to vertical the second growing season, the moderate and heavy the fourth growing season, and the severely snow bent the sixth growing season (we considered any angle under 5 degrees vertical).

Table 1.--*Angle from vertical of snow-bent trees by original snow-bend category and year*

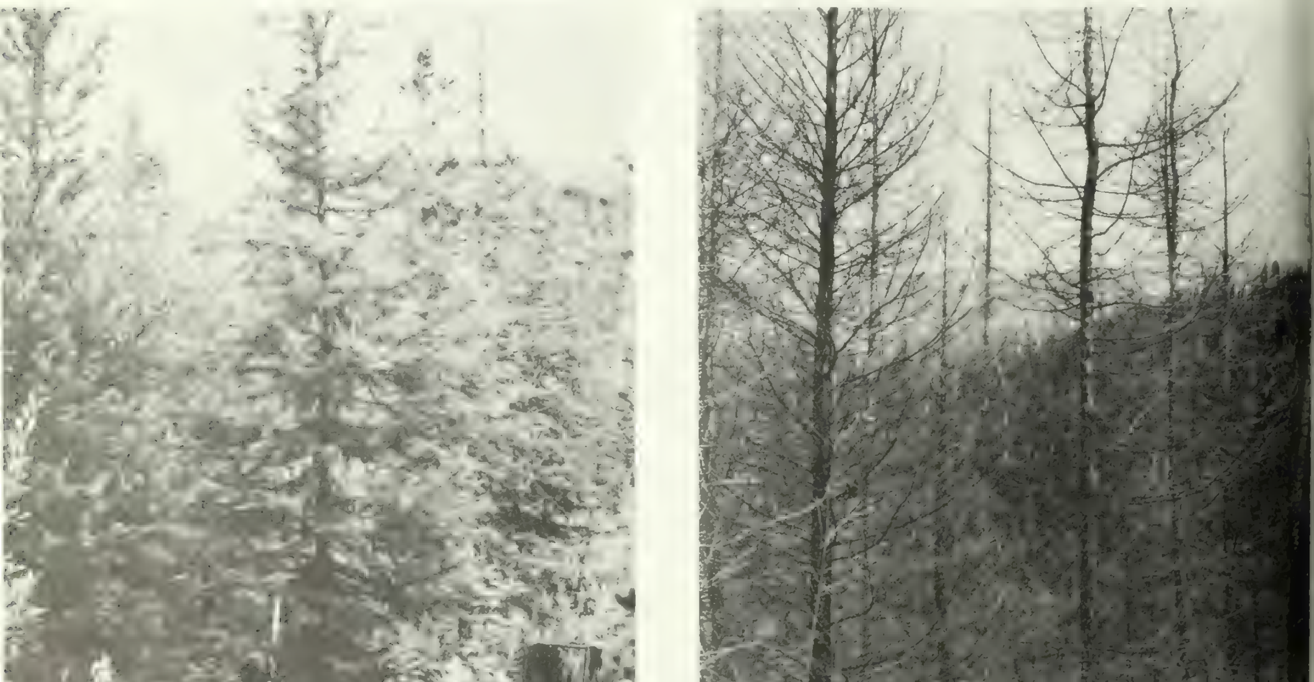
| | Snow-bend angle from vertical | | | | | |
|---|---|---|---|---|---|---|
| Snow-bend category | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 |
| | *Degrees* | | | | | |
| Slight | 15 | 0 | 1 | 0 | 0 | 0 |
| Moderate | 31 | 7 | 5 | 3 | 3 | 1 |
| Heavy | 56 | 13 | 6 | 3 | 0 | 0 |
| Severe | 67 | 30 | 20 | 10 | 5 | 4 |



1966

1967

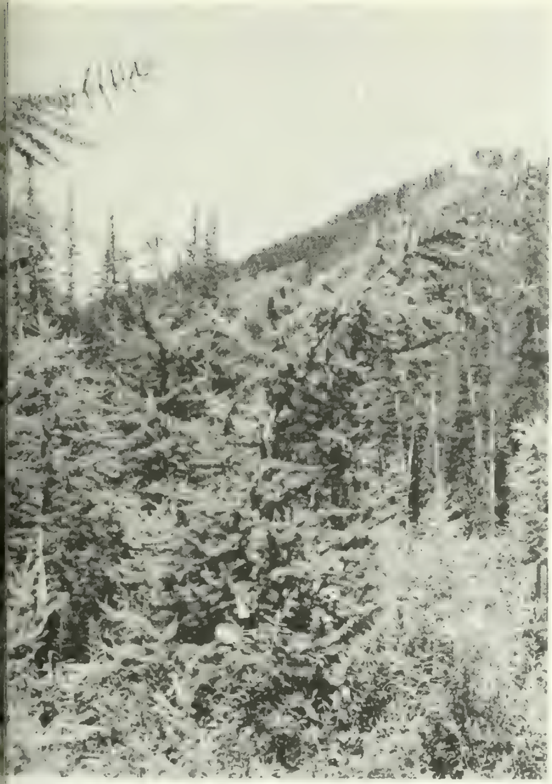
*Photo series A = slight snow bend.*



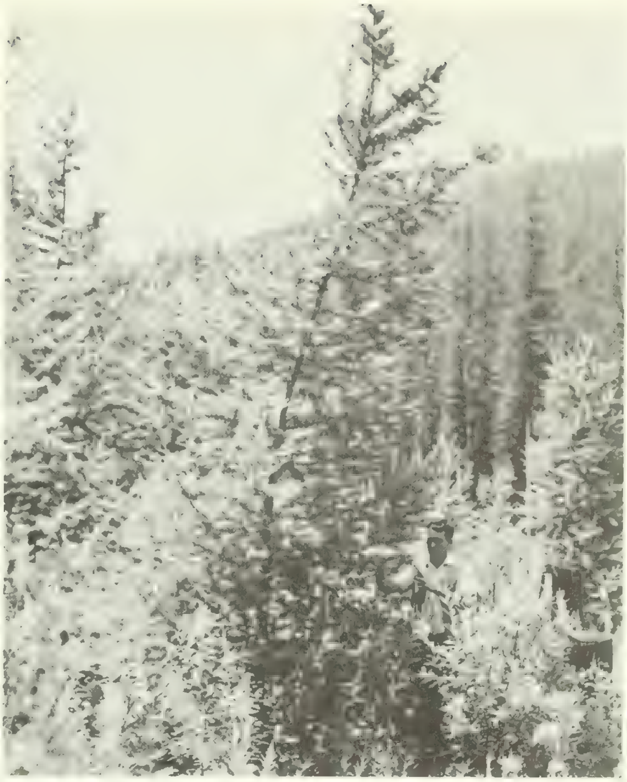
1970

1976

*Figure 1.--Initial snow-bend categories and trees' rate and extent of recovery during an 11-year period. Trees were 13 years old when initially snow bent.*

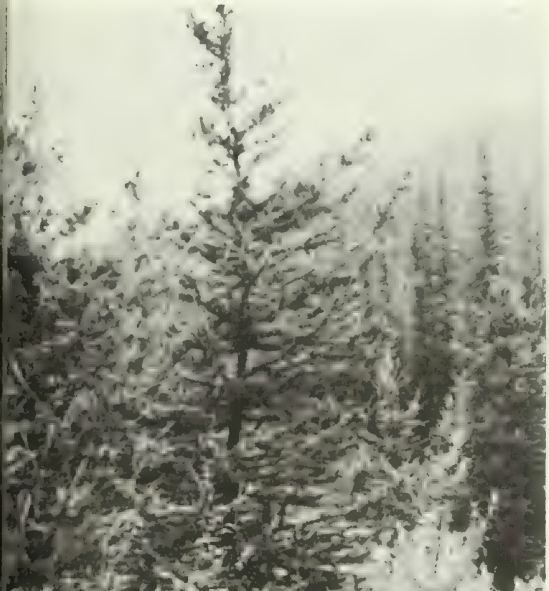


1966

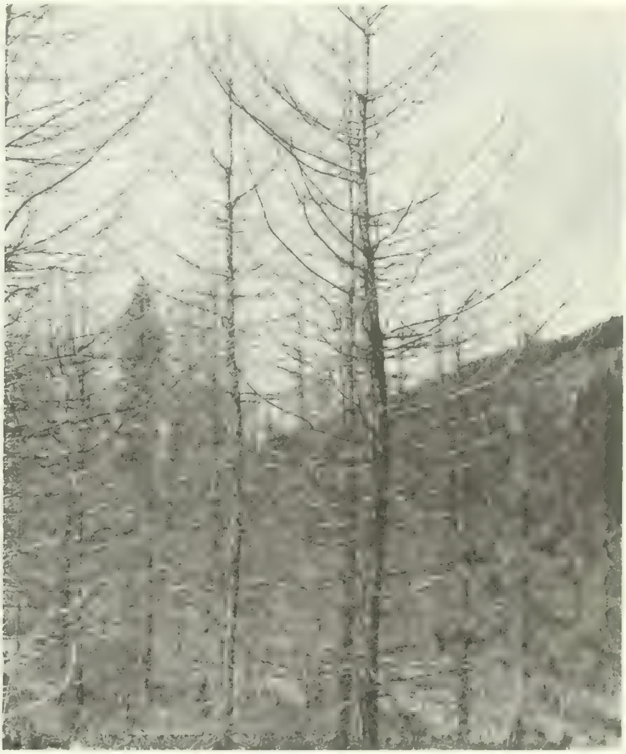


1967

*Photo series B = moderate snow bend.*

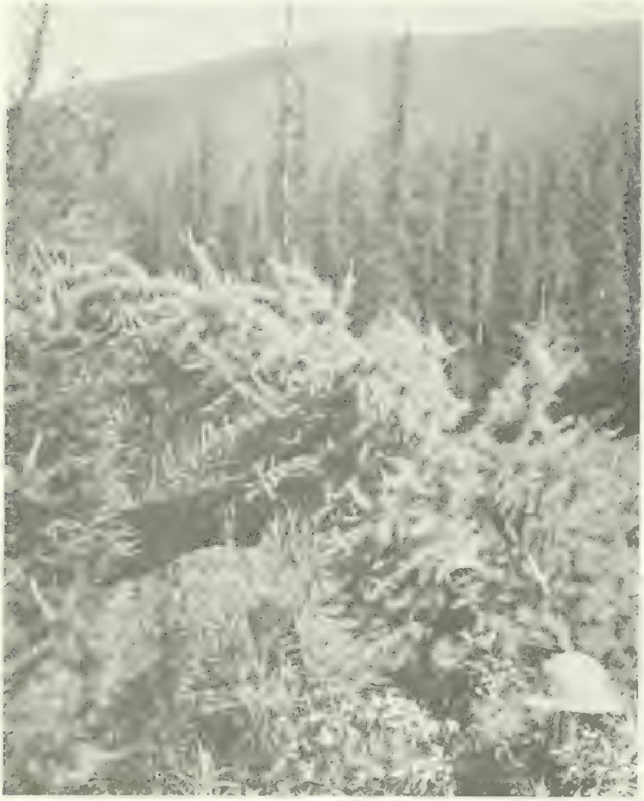


1970

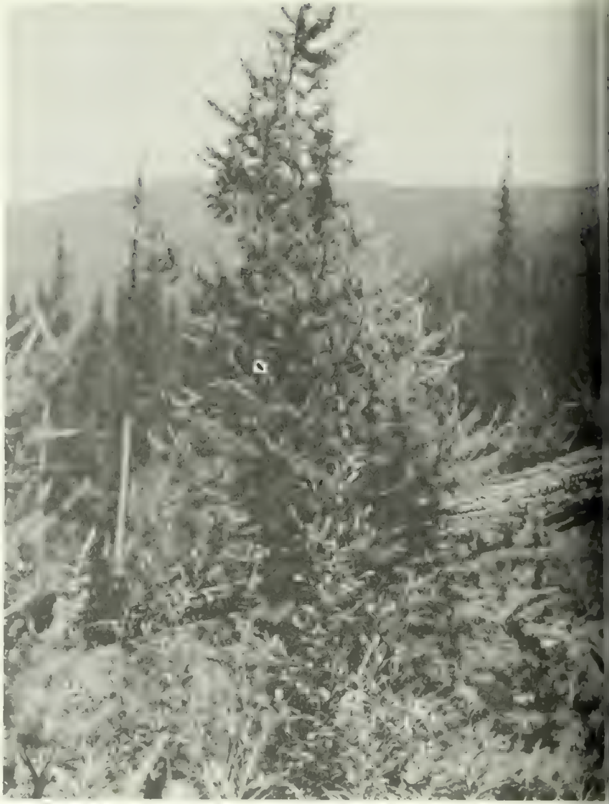


1976

*Fig. 1* con.

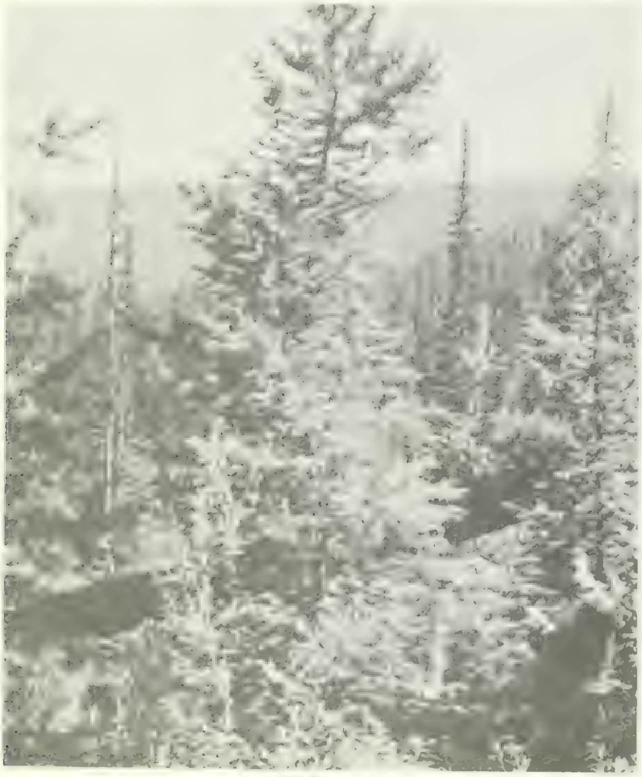


1966

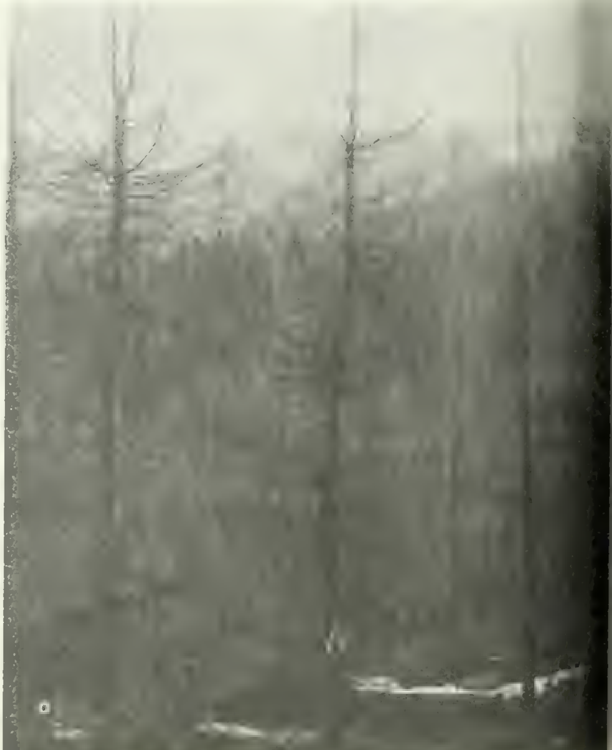


1967

*Photo series C = heavy snow bend.*

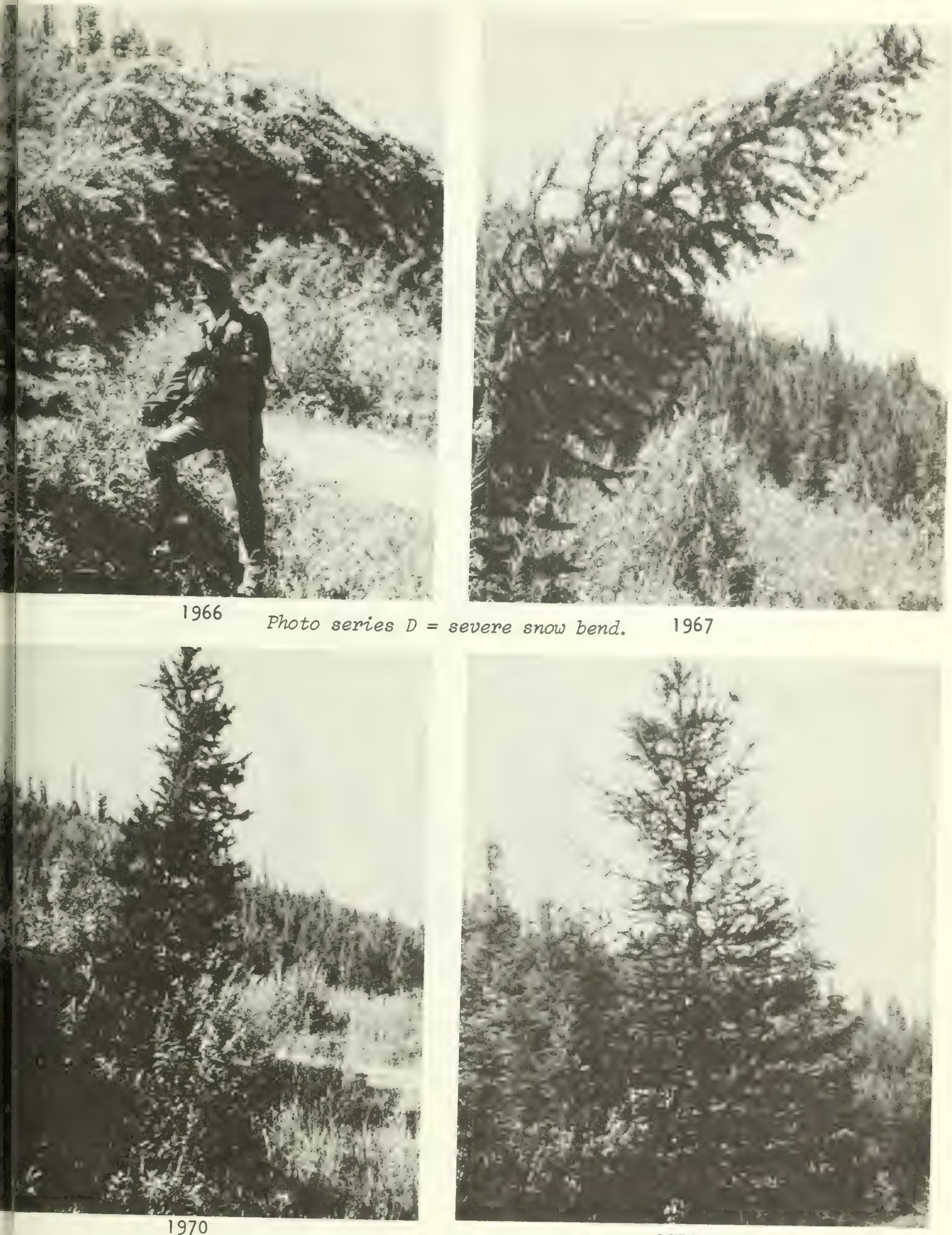


1970



1976

*Fig. 1* con.



1966

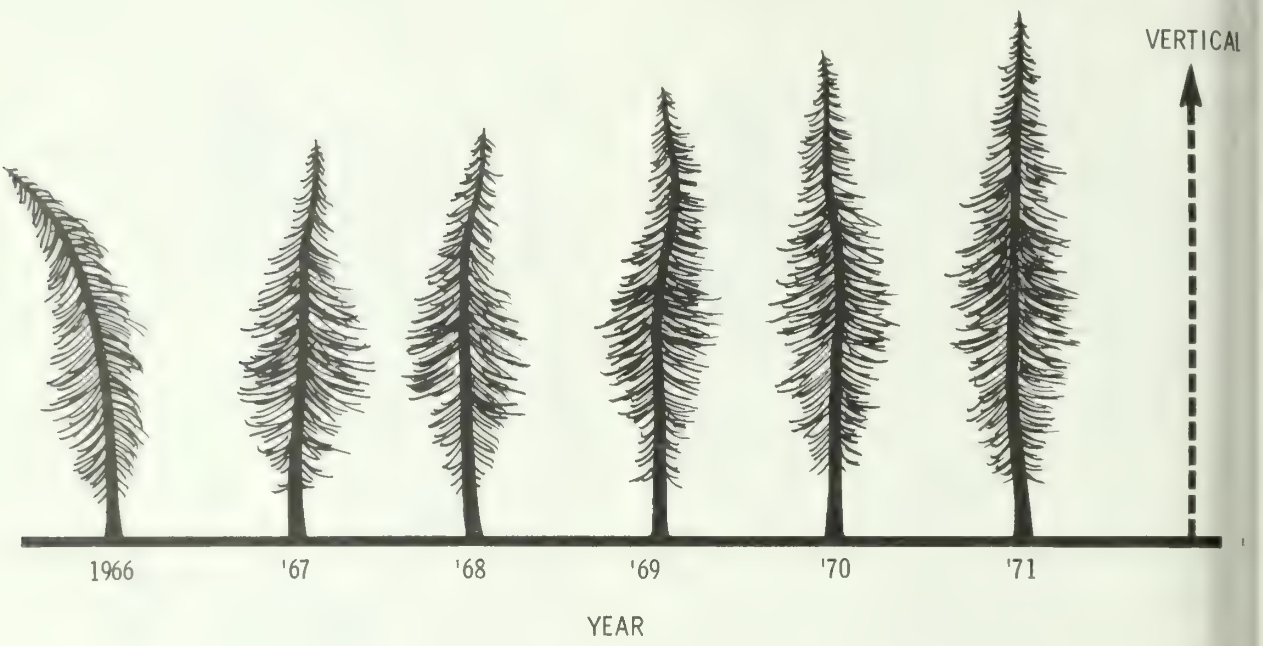
*Photo series D = severe snow bend.*

1967

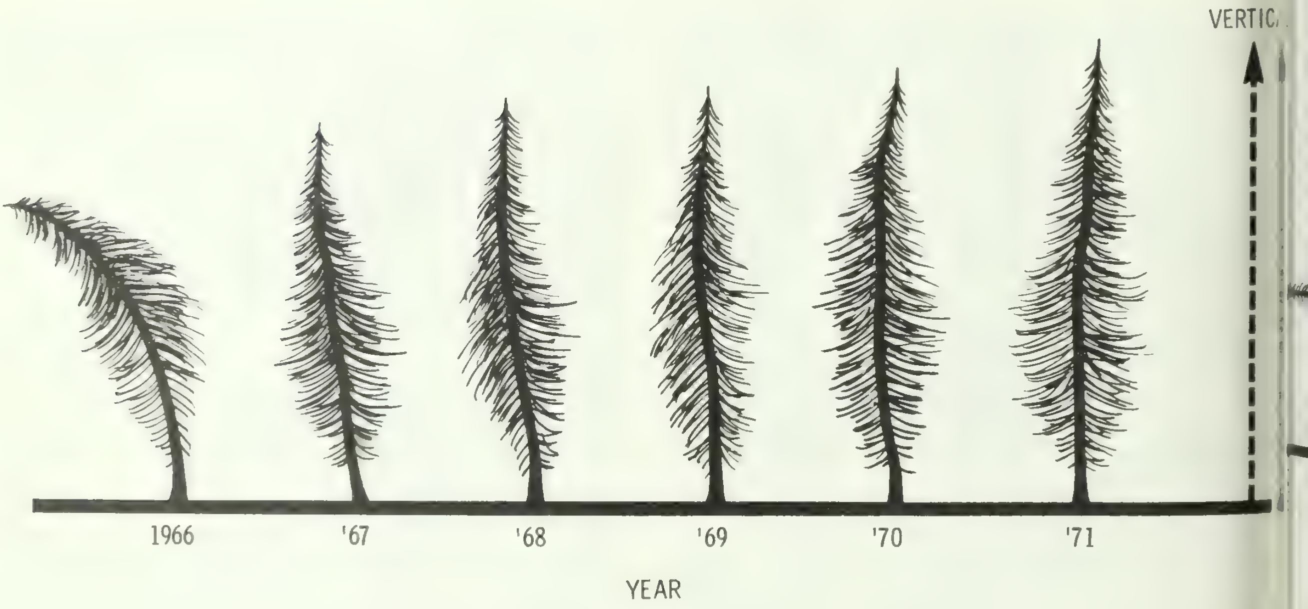
1970

1976

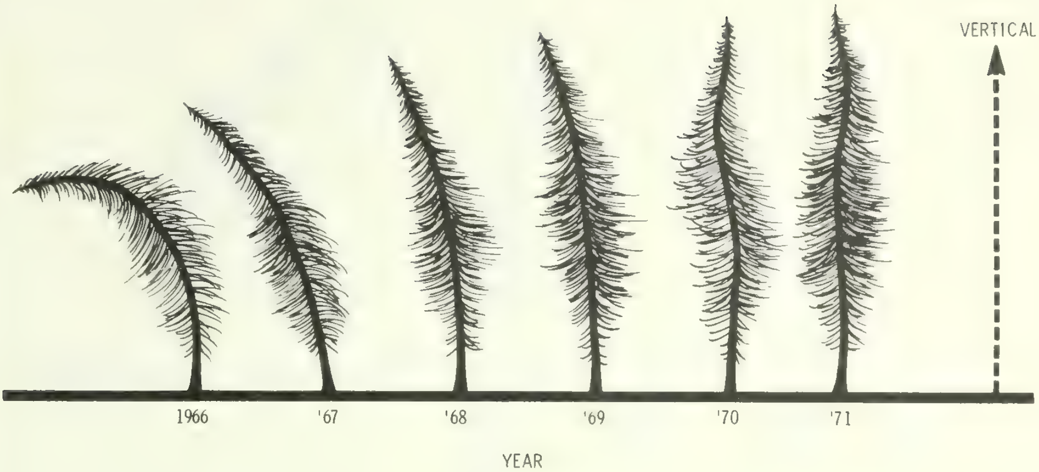
Figure 2.--Schematics from actual examples of tree recovery by snow-bend category and year, with emphasis on bole configuration.



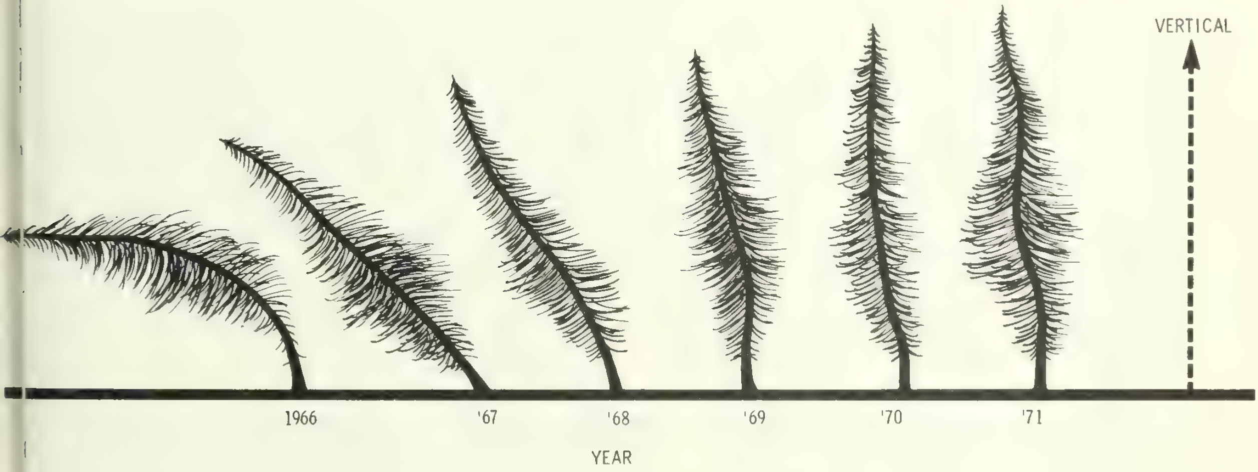
*Schematic A = slight snow bend.*



*Schematic B = moderate snow bend.*

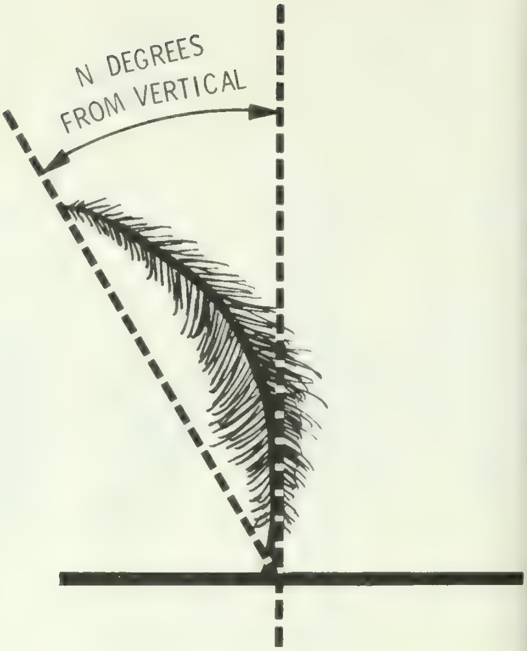


*Schematic C = heavy snow bend.*



*Schematic D = severe snow bend.*

Figure 3.--How we measured snow-bend angle from vertical.

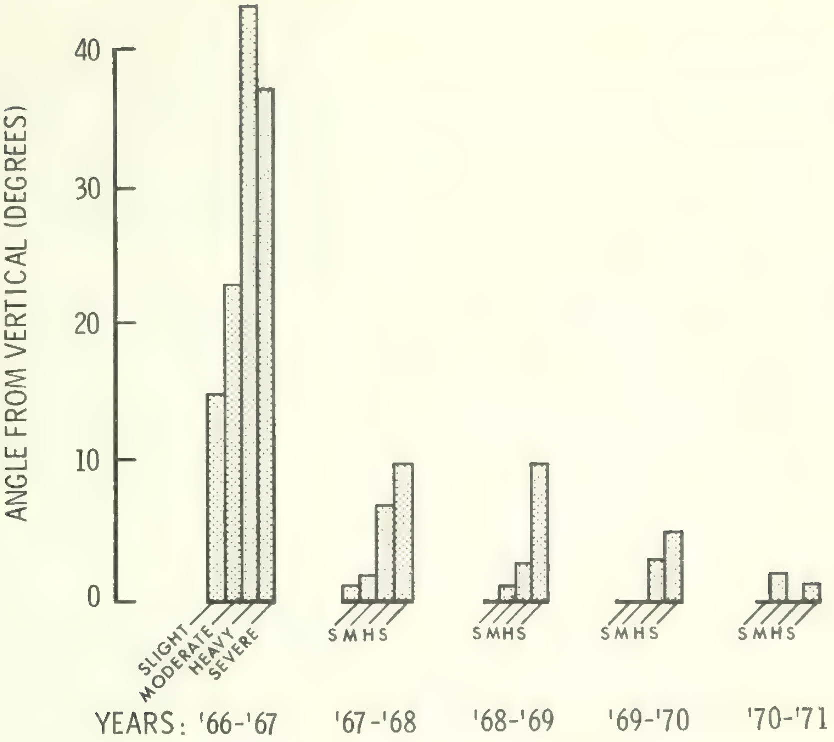


All the trees rapidly approached vertica with the most dramatic changes (percentage) occurring in the most heavily snow-bent trees in the first year (fig. 4). The annual chang in angle differed significantly between initi snow-bend categories. However, we detected n significant differences between tree crown classes--dominant and nondominant trees recovered at the same rates.

As shown schematically in figure 5, tree tended to overcorrect in response to snow ben The terminal leader grew vertically, regardle of the angle of the bole. In the meantime, th bole itself reapproached a vertical position. This in turn threw the terminal into a revers angle from the initial snow-bend angle. The next season, the process reversed itself and crooked boles resulted. Usually, the crooks that developed from this process ameliorated. It is doubtful if there will be any significa long-term effect of this overcorrection proce

Snow bend stimulated abnormal needle tufting in larch. Tufts (or clumps) of needl were observed on snow-bent trees, with few or none on the slightly snow-bent and many on the most heavily snow-bent trees. Minor amounts this abnormality were observed as soon as one year (1967) after the snow, then gradually bui ing up and becoming most pronounced in the 4th and 5th seasons after the snow. This abno mality then gradually subsided until the 11th season when no more tufting was observed. Snow damage apparently triggered physiological processes that resulted in adventitious growth most likely a survival mechanism for larch.

*igure 4.--Annual ngle change during he period of ecuperation from now bend by snow-end category.*



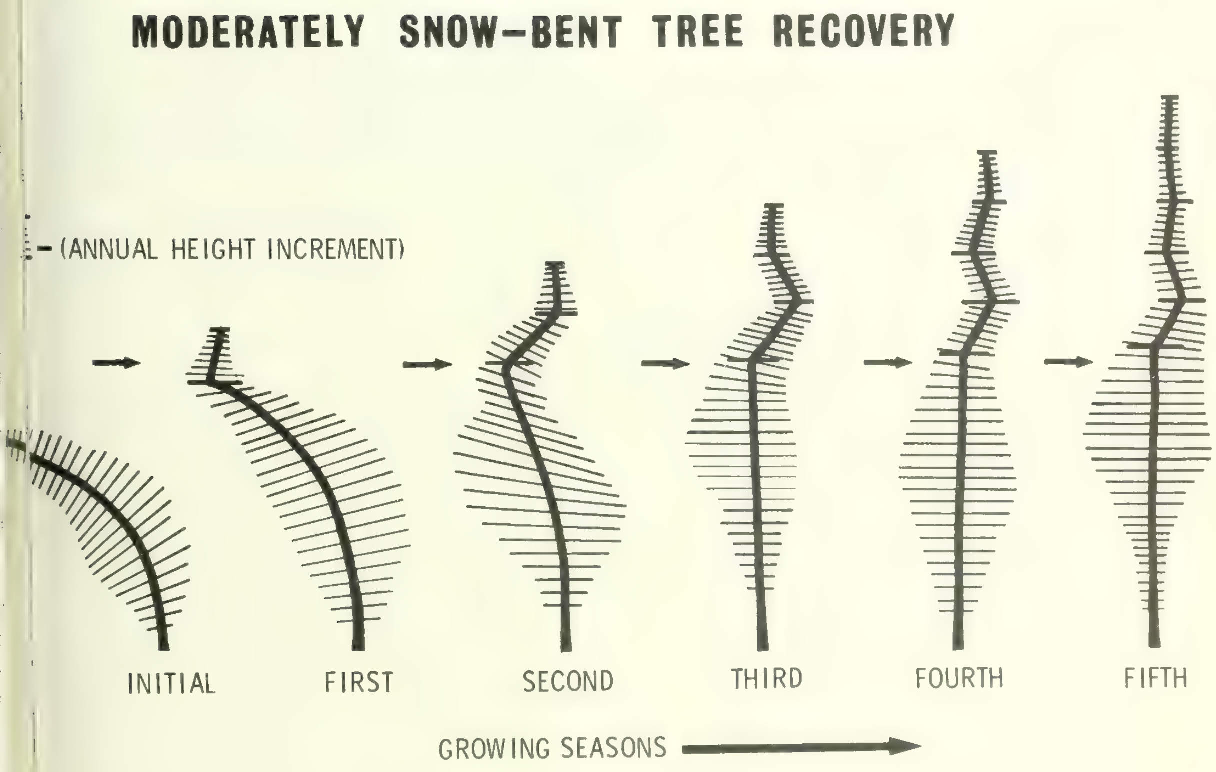


*Figure 5.--Schematic illustration of snow-bend recovery showing the tendency of larch trees to overcorrect and in the process produce crooks in the boles.*

## What do we conclude about snow-bend?

Don't despair if you see your young larc flattened by a late spring snow. All is not lost. In all likelihood they will recover. There will be some crooked boles for a while but even they will not be a significant probl a decade or so later. This corresponds to similar observations of conifers in the Casca Mountains (Williams 1966).

We speculate that successive years of la spring snows would produce a much less favorab recovery. The more severely snow-bent trees would likely gather a heavier load of snow whi in that position, thus perpetuating the condition. As a result we would expect many malformed trees. However, that didn't happen in the course of this study and likely has a low probability of happening.

A word of caution--the results reported here are from a forest that was not heavily overstocked and that had the advantages of yo Hence, the trees were in excellent condition. Had these trees been very recently thinned fr a heavily overstocked condition, or had they been an older age, recovery might have been much less favorable.

Young larch are very supple and capable of rapid recovery. The strong apical dominan characteristics of larch contribute heavily toward its ability to recover from snow, as well as a host of other physical and biologica factors.

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Schmidt, Wyman C., and Jack A. Schmidt.
1979. Recovery of snow-bent young western larch. USDA For. Serv. Gen. Tech. Rep. INT-54, 13 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

This paper illustrates how much, how long it takes, and the method in which young western larch responds to snow bend. A 13-year-old vigorous larch stand was flattened by a heavy, wet snow in June 1966 in northwestern Montana. We recorded photographically how two different crown classes (dominant and nondominant) of young larch subjected to four levels of snow bend (slight to severe) recuperated during the 11-year period following damage. The vigorous condition of the supple young larch contributed greatly to their remarkable recover.

KEYWORDS: *Larix occidentalis*, western larch, snow bend, snow damage, crooked boles.

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# LARCH CASEBEARER
# IN WESTERN LARCH FORESTS

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# RESEARCH SUMMARY

Larch casebearer is the most serious insect enemy of western larch. Introduced into the United States from Europe before 1900, the casebearer was discovered in Idaho in 1957, and has spread throughout most of the botanical range of its host tree. The casebearer is firmly established in the western larch ecosystem and probably in time it will assume the status of a native insect pest.

During 1957 to 1967, the casebearer population built up and spread unchecked. Since then, two droughts in 1967 and 1973 drastically reduced casebearer numbers, especially in northern Idaho. Each time, casebearer populations have taken 3 to 4 years to build up to their former levels.

Although tree mortality has occurred, the most serious damage caused by casebearer defoliation has been loss of growth. In severe infestations of 5-year duration, loss of radial increment can amount to as much as 97 percent.

In 1960, a program was started to establish biological control of the casebearer by introducing the parasite *Agathis pumila*, a native of Europe. In the 1970's, six additional exotic parasites were introduced into western larch forests. Of these, *Chrysocharis laricinellae* promises to be an effective biocontrol agent along with *A. pumila*. In the aggregate, native parasites exert some control, and birds are probably important predators along with mites and hemipterous bugs.

Several insecticides controlled the casebearer in field tests, but only technical grade malathion applied at a dosage rate of 8 fluid ounces per acre (585 cc/ha) is registered for use. Biological control, rather than use of chemicals, is advocated to keep the casebearer at generally acceptable levels. As in the case of native insect pests, forest managers will have to evaluate each epidemic and decide how to deal with it.

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# INTRODUCTION

Larch casebearer, *Coleophora laricella* (Hbn.), and other closely related species, re distributed worldwide on nearly every species of larch (*Larix* sp.). *Coleophora aricella* was introduced into the United States from Europe, presumably on planting tock of European larch, *Larix decidua* Mill. It was first found in Northampton, Mass., n 1886 on European larch (Hagen 1886), but quickly established itself on native Amerian larch (tamarack), *Larix laricina* (DuRoi) K. Koch. The casebearer's spread in eastrn North America was rapid. Patch (1906) reported infestations in Maine, and Fletcher 1906) noted its appearance in Ottawa, Canada, in 1905. In 1942, the casebearer was und in Newfoundland, Canada.

Westward spread has been more rapid in the southern part of the American larch ange. In the early 1920's, it was found near Ann Arbor, Mich., and it was recorded northeastern Wisconsin in 1939. By 1952, the casebearer had spread westward as far s St. Paul, Minn.

In Canada, the casebearer was found at Sault St. Marie, Ontario, in 1942[1] and Port thur, Ontario, in 1947.[2] It was first recorded in southeastern Manitoba by Elliot d Hildahl (1966).

Until 1957, the possibility of western larch, *Larix occidentalis* Nutt., becoming fested seemed remote. Even though the range of American larch is transcontinental rough Canada, a wide gap separates its habitat in the provinces of Alberta and British lumbia from the northern extent of western larch. Nevertheless, in 1957 an outbreak f the casebearer was discovered in the vicinity of St. Maries, Idaho, approximately 700 miles distant from the last-reported infestation in Minnesota.

How the infestation became established in this area is a matter of conjecture. cause the only means of natural dispersal is in the adult (moth) stage, the most ausible explanation would seem to be that the casebearer was introduced in the larval age on planting stock from eastern States; however, there is no knowledge of any erican or European larch in the vicinity of St. Maries. Another possibility is that ult insects were transported into Idaho by railroad. Milwaukee Railroad trains, origiting in Chicago, Ill., travel through casebearer-infested portions of Wisconsin and nnesota on their way west. The railroad operates a freight-marshalling yard at St. ries, where freight trains are held for varying lengths of time while being remade; tis may have provided the opportunity for casebearer moths to escape into surrounding rch stands. It is also unknown how long the casebearer was present in Idaho before is discovery. The large populations and extent of visible defoliation suggested that i became established many years before 1957.

---

[1] Canadian Insect Pest Review 21(1):25. 1943.

[2] Canadian Insect Pest Review 25(2):136-137. 1947.

Prior to the casebearer's invasion, western larch was relatively insect pest-free, compared with most of its coniferous associates, and its insect enemies received sporadic attention. The only recorded outbreaks are of several defoliating insects. Evenden (1922) reported a flareup of two previously undescribed sawflies, the two-line larch sawfly (*Anoplonyx occidens* Ross) and the western larch sawfly (*Anoplonyx laricivorus* Roh. and Midd.). During the 1930's the larch sawfly (*Pristiphora erichson* Hartig) appeared in western larch forests, along with the larch budmoth (*Zeiraphera griseana* Hbn.) (Keen 1952). From 1955 through 1957, several defoliators flared up simultaneously, including the two-lined and western larch sawflies, larch budmoth, and a geometrid (*Semiothisa sexmaculata* Pack.) (Denton 1958). These outbreaks subsided in 1958 without causing appreciable damage. During the 1960's there were occasional loca ized flareups of the larch budmoth and larch sawfly; however, until the advent of the larch casebearer no tree mortality resulting from any defoliator outbreak has been reported in western larch forests.

In addition to the larch casebearer, the western spruce budworm (*Choristoneura occidentalis* Freeman) was found damaging western larch in Montana. Normally, the budworm's diet is the current year's foliage of several conifers. However, since 1962 th budworm has been found not only feeding on the foliage of larch but also severing the stems of the current-year terminal and lateral shoots. This reduces juvenile height growth and detracts from tree form (Fellin and Schmidt 1967, Schmidt and Fellin 1970). The larvae also damage cones and seeds (Fellin and Shearer 1968).

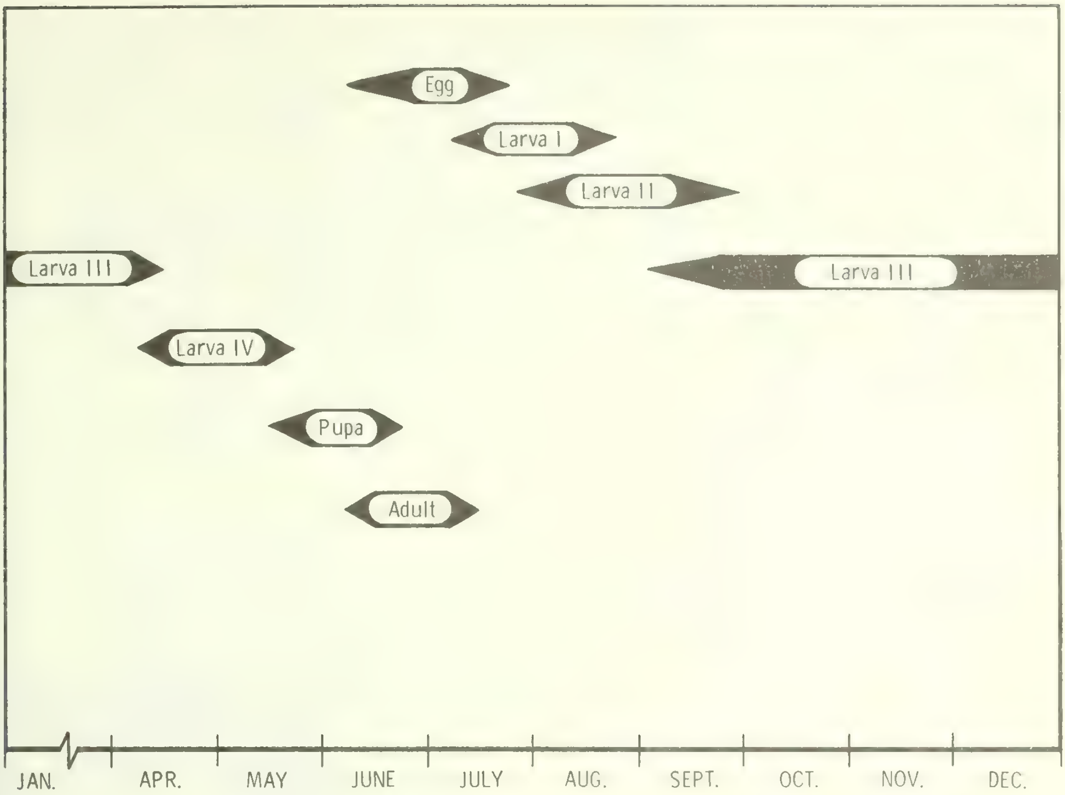
This publication brings together the knowledge accumulated on the biology, ecolog and control of the larch casebearer since its discovery in western larch forests. A considerable amount of this knowledge has not been previously published. Although thi paper is concerned primarily with the casebearer in western North America, studies in eastern North America and in Europe are cited where pertinent.

# DESCRIPTION, LIFE HISTORY, AND HABITS

## Egg

The general period of occurrence of larch casebearer life stages in western larch forests is shown in figure 1. Larch casebearer eggs are laid from early June until late July, depending upon seasonal weather conditions. Newly deposited eggs are yellow ish in color, becoming cinnamon colored as the embryo develops. Under magnification, eggs resemble inverted jelly molds, with 12 to 14 lateral ridges extending from the apex to the base (fig. 2). The flat lower side is cemented to a needle by a glassy, transparent substance.

When casebearer populations are low, eggs are usually deposited one to a needle; however, when populations are high as many as four eggs are found per needle (table 1). Nearly all eggs are deposited on the lower ribbed sides of the needles, and the majority are placed on the distal half. In one study (Denton 1964), 11 percent of all needles examined contained one or more eggs. Of the needles bearing eggs, 79 percent had one egg, 16 percent had two eggs, 3 percent had three eggs, and 1 percent had four eggs (table 1). Only 53 percent of the eggs hatched and predation was suspected as the major cause why nearly half, or 47 percent, of the eggs remained unhatched. This is discussed in the section on BIOLOGICAL CONTROL.



igure 1.--General period of occurrence of larch casebearer life stages in western larch forests.

Fi re 2.--Larch casebearer egg.

[illegible] Idaho

| [illegible] (tree) | Branches sampled | Needle fascicles | Total needles |  | Needles having |  |  |  | Total eggs |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  | First crop | Second crop | 1 egg | 2 eggs | 3 eggs | 4 eggs | Hatched | Unhatched |
| Number |  |  |  |  |  |  |  |  |  |  |
| 1 | 4 | 20 | 858 | 363 | 114 | 32 | 6 | 2 | 87 | 117 |
| 2 | 4 | 20 | 856 | 385 | 113 | 22 | 9 | 0 | 135 | 49 |
| 3 | 4 | 20 | 672 | 0 | 35 | 0 | 1 | 0 | 26 | 12 |
| 4 | 4 | 20 | 638 | 0 | 75 | 15 | 4 | 7 | 39 | 106 |
| 5 | 4 | 20 | 703 | 0 | 60 | 15 | 0 | 0 | 71 | 19 |
| 6 | 4 | 20 | 687 | 106 | 93 | 12 | 1 | 0 | 105 | 15 |
| 7 | 4 | 20 | 792 | [illegible] | 73 | 18 | 2 | 2 | 29 | 94 |
| 8 | 4 | 20 | 799 | 26 | 68 | 8 | 2 | 1 | 51 | 43 |
| 9 | 4 | 20 | 872 | 0 | 60 | 19 | 5 | 1 | 52 | 65 |
| Totals | 36 | 180 | 6,877 | 880 | 691 | 141 | 30 | 13 | 595 | 520 |

[1] Only 10 fascicles produced a second crop of needles.
[2] Only 5 fascicles produced a second crop of needles.
[3] Total number of needles for 55 fascicles.

Viable eggs hatch after about 2 weeks. In the East, in oviposition experiments a constant temperatures, Daviault (1949) found that the incubation period varied from 20 days at 62.5°F (16.9°C) to 13 days at 73°F (22.8°C). From these data, he calculate the development zero at 51.8°F (11°C). Quednau (1967) reported an incubation period o 40 days at 55°F (12.8°C) and 12 days at 80° to 85°F (27.2° to 29.4°C). Hatching of eg did not occur above 85°F (29.4°C) or below 55°F (12.8°C).

## Larva

When the eggs hatch, the very young (first and second instar) larvae are needle miners. First instar larvae average 0.04 inch (1 mm) in length. Mature larvae are about 0.2 inch (5 mm) long and dark reddish-brown with black heads and thoracic shield They remain largely concealed within cases made from sections of needles. Cases made from western larch needles are straw-colored and rectangular (fig. 3), becoming light grey and cigar-shaped at the time the insects pupate.

Upon hatching, the larva bores directly into the needle through the bottom of the eggshell and feeds for about 2 months inside the needle. The larva mines obliquely in the needle to the opposite side (upper or lower as the case may be), then along the ed either toward or away from the tip. The larva continues to mine along the edge of the needle until the first molt.

If two larvae are mining in the same needle and one tunnels into the mine of another, it usually dies--probably because it cannot mine farther without the restrictive walls to push against. When several larvae mine a single needle, those most distally situated usually die because of desiccation of the needle.

After the larva molts to the second instar, it usually doubles back and enlarges the mine by feeding alongside the original one. At this time, the mined portion is dis cernible as a whitish line, usually on the upper side of the needle. Also, during the second instar the larva becomes capable of independent movement and may leave small needles or drying foliage to begin a new mine elsewhere.

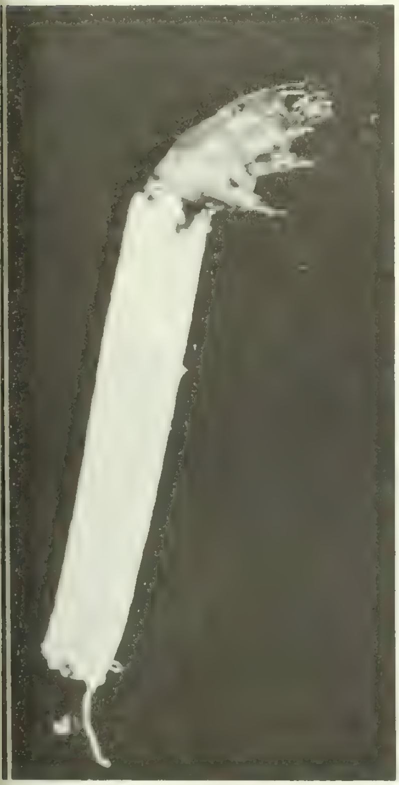
After hollowing a needle, the larva constructs a case by lining the inside of the mined section with silk and chewing the tip and basal portions free from the rest of the needle. It then moves about with only the head and thoracic legs showing (fig. 3). It does not drag the case, but carries it lifted clear by curving its body upwards.

Beginning in mid-to late August, the larva feeds externally upon the foliage in he third instar. It fastens its case firmly to a needle with a pad of silk and then ines the interior as far as it can reach in both directions without actually leaving he case. After mining one needle, the larva chews its case free and moves on to nother.

The casebearer spends the winter as an immature, third-instar larva inside its ase. Cessation of feeding varies considerably depending upon weather conditions, but egins soon after the first frost of the fall, usually in October. As the needles of lder fascicles begin to fade prior to being shed, the larvae move out to the needles f new terminal shoots that remain green the longest. Thus, the larvae tend to be conentrated on the outermost portions of branches as they prepare for hibernation.

When ready for hibernation, the larva lines its case heavily with silk and fastens ie case securely with silk threads at the base of a fascicle. Larvae display a distinct regariousness and in a dense infestation clusters of hibernating casebearers may be ound on the twigs (fig. 4).

The larva resumes feeding in the spring shortly after the new needles appear--about id-April at lower elevations. Prior to freeing its case, the larva molts to the fourth nstar. It then feeds heavily for about 1 month before reaching its full development.



*igure 3.--Larch casebearer larva protruding from its case.*

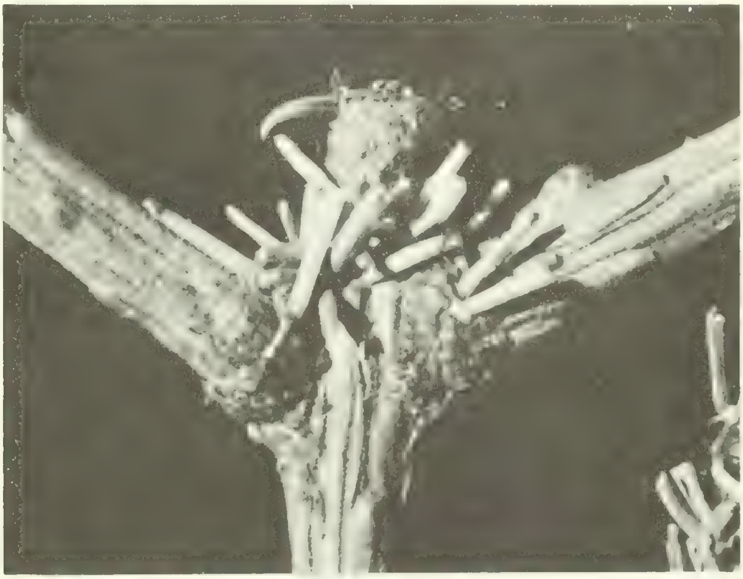


*Figure 4.--Overwintering larch casebearer larvae in their cases attached to western larch twigs.*

## Pupa

The pupa is chocolate brown in color, and has no distinctive markings or features. Pupation has been observed as early as May 15, but generally it occurs in late May or early June. When the larva completes its development it usually fastens itself in the center of a fascicle (fig. 5). In heavy infestations, larvae display the same gregariousness as during hibernation.

After fastening the anterior end, the larva turns around in the case to pupate, first closing the rear opening with a few strands of silk. This period of preparation, from cessation of feeding to pupation, occupies about 2 or 3 days. The pupation period averages about 2 weeks.

## Adult

Larch casebearer moths are silvery to greyish-brown with no conspicuous markings. The wings are narrow and fringed with long, slender, hair-like scales. The wing expanse is about 0.4 inch (10 mm). The sides of the abdomen of a male appear almost straight and parallel, and the presence of claspers gives the anal extremity a bifurcated appearance. Females are lighter grey than males and the sides of the abdomen are rounded, giving a more robust appearance. The tip of the abdomen is abruptly truncated.

The emerging adult first unseals the posterior opening of the case by breaking the silk threads. The head and antennae are pushed free, then the wings and legs. For a few minutes the wings are held vertically above the body to permit the tissues to take shape before the chitin hardens, and then are folded roof-like over the abdomen.

Adults are capable of agile movement on the foliage, but are more often observed in the characteristic resting pose on the ends of the needles (fig. 6). They are easily disturbed, but they are not strong fliers and usually alight after only a short flight.

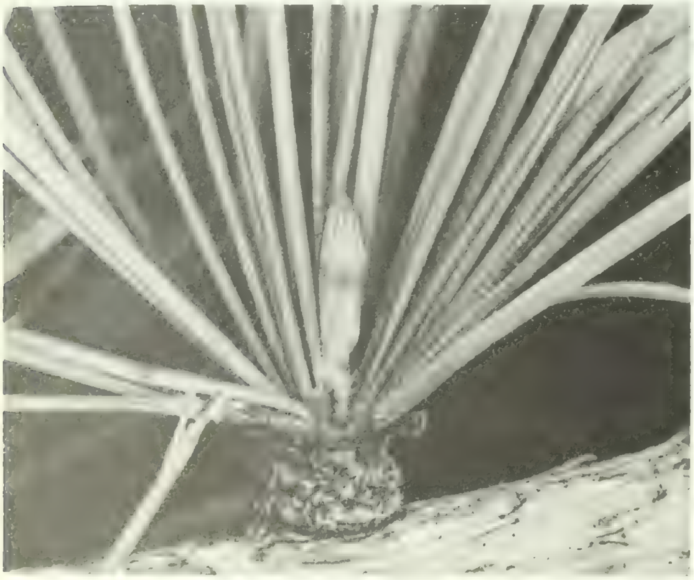


*Figure 5.--Larch casebearer pupal case attached in the center of a needle fascicle.*

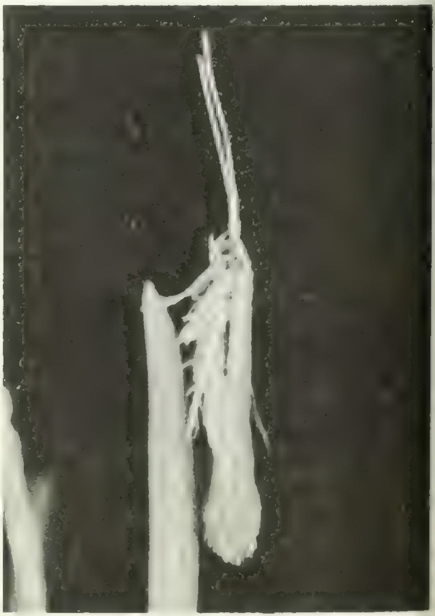


*Figure 6.--Larch casebearer moth in characteristic posture on a needle.*

In laboratory and greenhouse experiments, mating was observed within a day or two fter the emergence of females. Oviposition began a few hours after mating and continued or as long as 2 weeks. The number of eggs laid by females in confinement varied coniderably from 20 to 84, or an average of 52 eggs per female.

In the West, the casebearer's only host is *Larix* species. Attempts to force-rear asebearer larvae on other coniferous species have not been successful. In greenhouse xperiments, fourth-instar casebearer larvae were placed on grand fir (*Abies grandis* Dougl.) Lindl), Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), westrn hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western white pine (*Pinus monticola* ougl.). Although the larvae fastened themselves to the foliage of all these species nd began to mine the needles, none completed its development and either died or left he foliage in search of its preferred host.

In Europe, several workers suggest that Douglas-fir is a possible host of the casebearer (Guass 1957, Luitjes 1971, Voute 1952). They did not make it clear whether the asebearer completed a generation; however, Guass reported high larval mortality which was attributed to the unsuitability of Douglas-fir needles as a food source.

# DISTRIBUTION AND CHRONOLOGY OF OUTBREAKS IN THE WEST

After the casebearer outbreak was discovered in 1957, ground surveys showed that visible defoliation occurred throughout a gross area of 170 mi$^2$ (440 km$^2$) southeast of ake Coeur d'Alene, Idaho. Within a 10-mile (16.1-km) radius of St. Maries, overwintering populations were as much as 310 larvae per 100 fascicles.

Eradication was advocated, but no insecticide had been tested except lime sulphur pplied from the ground as a dormant spray before the casebearer had broken hibernation. Also, the full extent of the casebearer's distribution was unknown.

In the spring of 1958, ground surveys were made to determine the casebearer's distribution beyond the area of visible defoliation. Spread was mainly to the north as far as Chewelah, Wash., and Sandpoint, Idaho. By 1959 the casebearer was found over practically all of the northern Idaho panhandle and northeastern Washington. It was obvious that the casebearer was firmly established in the western larch type and could not be eradicated.

From 1957 through 1959, the area of visible defoliation remained unchanged; however, in 1960 visible defoliation increased to 500 mi$^2$ (1,295 km$^2$), to 700 mi$^2$ (1,813 km$^2$) in 1961, and doubled to 1,440 mi$^2$ (3,730 km$^2$) in 1962. The casebearer was found first in Montana in 1961 east of Lookout Pass. The casebearer is distributed naturally only in the moth stage. In the early years, the fastest spread was to the north and northeast--probably because of prevailing winds. By 1970 the casebearer was distributed throughout most of the larch forests in the Northern Region of the Forest Service. It also invaded larch forests in British Columbia in 1966 (Andrews 1966).

Although somewhat slower, nevertheless the southward and westward spread of the casebearer has been persistent. It was found in southeastern Washington in the Blue Mountains in 1967, and spread to larch forests in northeastern Oregon. By 1974, the casebearer had bridged the gap to larch forests on the east slopes of the Cascade Mountain Range in western Washington and is now present throughout the range of western larch in Washington.

In 1977, the casebearer was discovered in low numbers in the Intermountain Region of the Forest Service at Cascade and Smiths Ferry, Idaho (Malcolm M. Furniss, personal communication). This is the southern limit of western larch in the State. There are only a few areas in the botanical range of western larch that remain to be infested (fig. 7).

In the Northern Region during the first 10 years from 1957 to 1967, climatic conditions were generally ideal to permit a tremendous buildup and spread of the casebearer. However, during the last 10-year period, 1967 to 1977, weather and climatic conditions have twice decimated casebearer populations.

In the summer of 1967, a drought occurred over most of western Montana, northern Idaho, and northeastern Washington and casebearer populations were reduced to low levels because of premature drying and needle drop of western larch foliage. Considerable additional overwintering mortality occurred in northern Idaho during the winter of 1968-1969 when temperatures reached record lows of -40° to -50°F (-40° to -45.6°C). In the areas checked, casebearer mortality averaged 55 percent, compared to about 10 percent in "normal" years.

By 1970, casebearer populations had increased to a level where heavy defoliation continued until 1973. In that year, a severe drought again drastically reduced casebearer populations, especially in northern Idaho. Populations have remained very low since then, but in 1977 population measurements indicate that the casebearer is beginning to build up again.

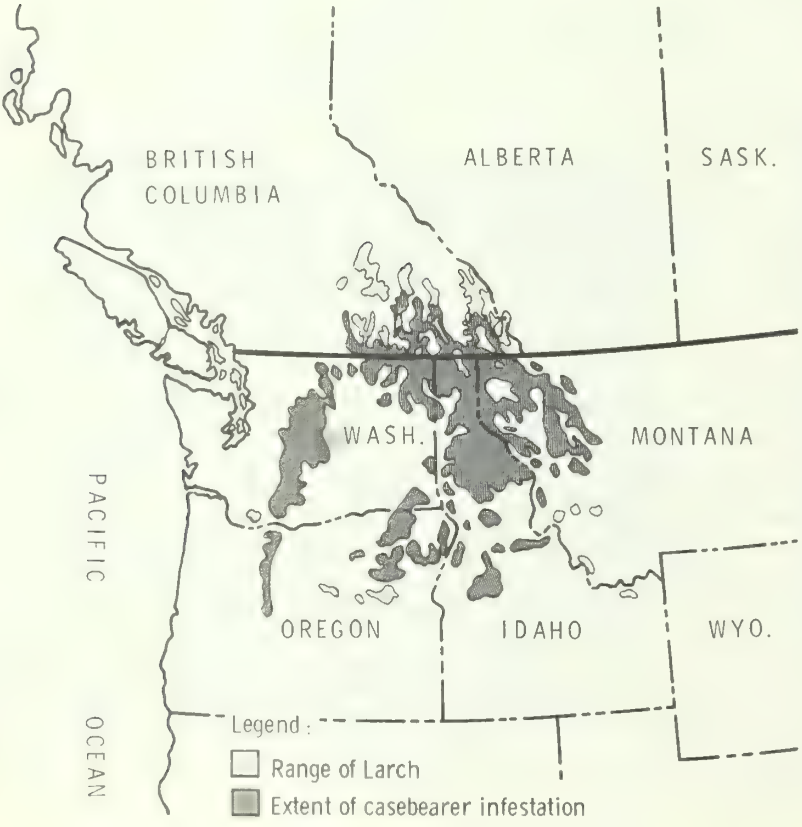


*Figure 7.--Botanical range of western larch and extent of larch casebearer infestation within that range.*

The course of the casebearer infestation in Montana has been different than in Idaho. Although the casebearer can be found throughout the larch forests, in some areas it seems incapable of increasing its numbers to the point where defoliation is even visible. For example, in traveling east on U.S. Highway 2, generally heavy defoliation has been observed from Bonners Ferry, Idaho, to Libby, Mont. However, from Libby to Kalispell, Mont., no visible defoliation has occurred over the years. Likewise, the casebearer was found in Pattee Canyon south of Missoula, Mont., in 1963--again defoliation has not been visible. Prior to the drought in 1967, widespread areas from the Idaho border east to Thompson Falls and St. Regis, Mont., sustained heavy defoliation. Since then casebearer populations have not built up to former levels.

The reasons for the foregoing phenomena are not entirely understood, although weather and climatic conditions are suspect. However, farther east in Montana very heavy defoliation has occurred in past years from around Flathead Lake north into Glacier National Park. It is known that in 1976 casebearer populations throughout these areas were greatly reduced by a very cold, wet spring. Thus, to date, weather conditions periodically seem to be the primary controlling agent in western larch forests.

# DISTRIBUTION WITHIN TREES AND STANDS

## Population Sampling

Reliable means of measuring larch casebearer populations are essential for predicting trends and impacts in various ecological and management situations. Population intensities are a measure of infestation, and are expressed in numbers of insects per unit of available food. In the case of western larch, the lateral fascicles, or spur shoots, are easily distinguished, relatively uniform in size, and form convenient foliage units to express casebearer densities. Trees are customarily sampled with an expandable pole pruner, which limits the sampling height to about 25 ft (7.6 m). Because larch trees are usually sampled at midcrown, tall trees above 50 ft (15.2 m) cannot be sampled by conventional means. Branches must be shot off, or the tree felled.

The overwintering casebearer stage is the most convenient to measure after larch trees have shed their needles because the hibernating larvae are motionless, tend to be clustered on the outermost portion of the branches, and the period for sampling extends from November to April. Overwintering casebearer measurements are particularly useful in determining annual population trends over wide geographical areas because branch samples can be collected and stored for population counts during the winter months.

To determine the total amount of parasitism (native parasites and introduced species), sampling must be done during the casebearer pupal stage in late May or early June. Customarily, casebearer populations have been sampled by taking four 18-inch (45.72 cm) branches per tree at midcrown and determining the number of casebearers per 100 fascicles from the distal end of the branch. This requires counting fascicles to determine a sample unit. From this, the average casebearer population density per 100 fascicles is determined for a plot, or stand of trees.

Theroux and Long (1978) developed a method for determining the cumulative lineal inches of branch necessary to obtain a uniform 100-fascicle sampling unit for a plot, thus eliminating the need to count the number of fascicles on each sample. They determined that western larch branches collected from 23 plots in northern Idaho and western Montana had a combined mean distribution of 3.13 fascicles per inch (1.23 fascicles per centimeter) of branch length. At this fascicle density, 32 inches (81.28 cm) of lineal growth would provide a sampling unit of 100 fascicles.

To allow for variation in fascicle density between plots and to maintain a uniform sampling procedure between plots, Theroux and Long recommended taking a cumulative 36 lineal inch (91.44 cm) sample of six 6-inch (15.24 cm) samples per branch as illustrated in figure 8. This would in most cases result in a small amount of excess sample length being collected per branch to ensure a mean 100-fascicle ±10 percent sampling unit for a plot.

After completing the sample collection, a 10-percent subsample of the samples for each plot would be used to calibrate the remaining samples to a 100-fascicle sampling unit for the plot. The authors gave the following example:

Plot sample:

10 trees
40 branches, 4 per tree at midcrown

Subsample calibration:

| *Subsample #* | *Fascicles* | *Inches* | *Fascicles/inch* |
|---|---|---|---|
| 1 | 100 | 33 | 3.03 |
| 2 | 100 | 29 | 3.45 |
| 3 | 100 | 30 | 3.33 |
| 4 | 100 | 31 | 3.23 |

With a mean fascicle density of 3.26/inch (1.28/cm) for the plot, the required sample length for the remaining samples would be:

$$\frac{100 \text{ fascicles}}{3.26} = 31 \text{ inches}^{1}$$

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[1] Sample length rounded off to nearest inch.

Efficiency was improved by using this sampling method; sampling was completed in one-half the time compared to when fascicles were counted.

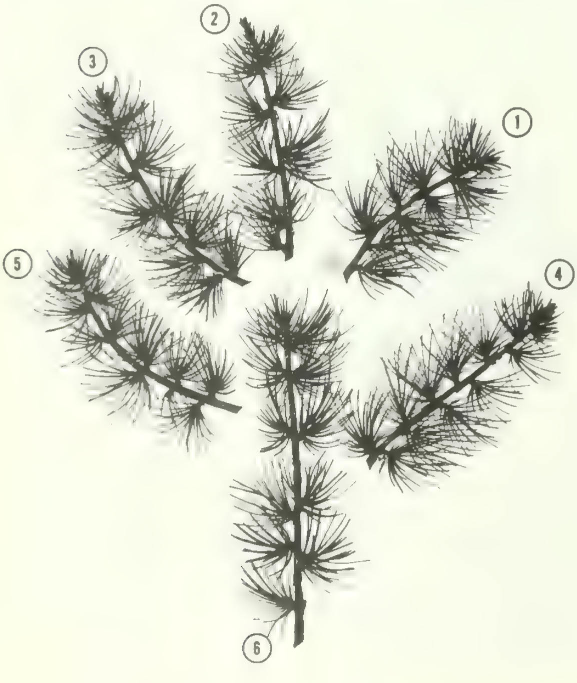


*Figure 8.--A 36-inch (91.4 cm) cumulative lineal sample of six 6-inch (15.24 cm) samples per branch to obtain 100 fascicles. (From Theroux and Long, Res. Note INT-245.)*

## Population within Trees and Stands

Larch casebearer populations vary considerably between branch segments, between branches, between various regions of the crown, and between stands. The relative distribution of infestation also varies according to the life stage of the insect, such s egg-laying habits of female moths and the migration patterns of the larvae.

Different branch segments are infested to varying degrees, primarily due to egg-aying habits. At the time of egg deposition in June, the new terminal growth shoots ave not fully developed and bear only single needles. Female moths have a preference or laying eggs on the outer areas of branches, but prefer fascicles to single needles. Thus, the majority of eggs are laid on the previous year's growth.

As was shown previously (LIFE HISTORY AND HABITS), the highest population density occurs on the outermost branch portions until the following spring when heavier feeding nd migration habits of maturing larvae cause them to be distributed farther back along he branches.

The distribution of infestation varies considerably between branches and crown evels until casebearer populations are uniformly heavy within a given stand or age, specially in smaller trees up to 40 to 50 ft (12.2 to 15.2 m) in height. In light to oderate infestation, generally there is a greater density of casebearers in the lower alf of the tree crown. Even so, it has been shown that the casebearer is not randomly istributed within a given portion of the crown; rather, the population is "clumped." hus, casebearer populations most nearly fit a negative binomial distribution (Garrell E. ong, personal communication).

In one experiment, the distribution of larch casebearer was determined in western larch that were more than 60 ft (18.3 m) in height. Twenty-three trees were felled that had a minimum height of 92 ft (28.1 m), with lower crowns extending not lower than 45 ft (13.7 m) above the ground. From 10 sample stations, equally spaced throughout the crown, six branches were cut. Casebearer populations were counted on the terminal 8 inches (20.3 cm) of each branch.

With reference to the amount of variation contained in cycles of certain lengths, wo types of casebearer distributions were apparent. Most trees exhibited a high degree of variability in casebearer density along the total length of the crown; i.e., cycles ith a period length approximating the crown length accounted for a large part of the otal variation within trees. For these trees, variation increased again for period engths ranging from about 9 ft (2.7 m) to about 15 ft (4.6 m). The other trees, generally with crown lengths less than 45 ft (13.7 m) exhibited peaks in variation associated with cycles of 16 to 27 ft (4.9 to 8.2 m) (Garrell E. Long, personal communication).

To determine the effects of larch casebearer on young western larch under different stand densities, a study was undertaken on the Coram Experimental Forest, Mont. The tudy was designed to determine casebearer-host relationships from the casebearer's nitial invasion through its epidemic cycle, utilizing five stocking densities (200, 60, 890, 1,740, and 10,000+ stems per acre) (494, 890, 2,199, 4,300, and 24,710 stems per ha).

In a 5- to 7-year period (1971 through 1977), casebearer populations were measured hree times annually: spring-feeding through 1976 (fig. 9); pupal, through 1977 (fig. 0); and fall-feeding through 1975 (fig. 11). Through 1975, analysis of variance showed ighly significant differences in mean casebearer densities between years, between sampling periods within years, and between stocking densities within seasons within years. n practically all measurements, the number of casebearers increased as the stocking ensity of western larch decreased.

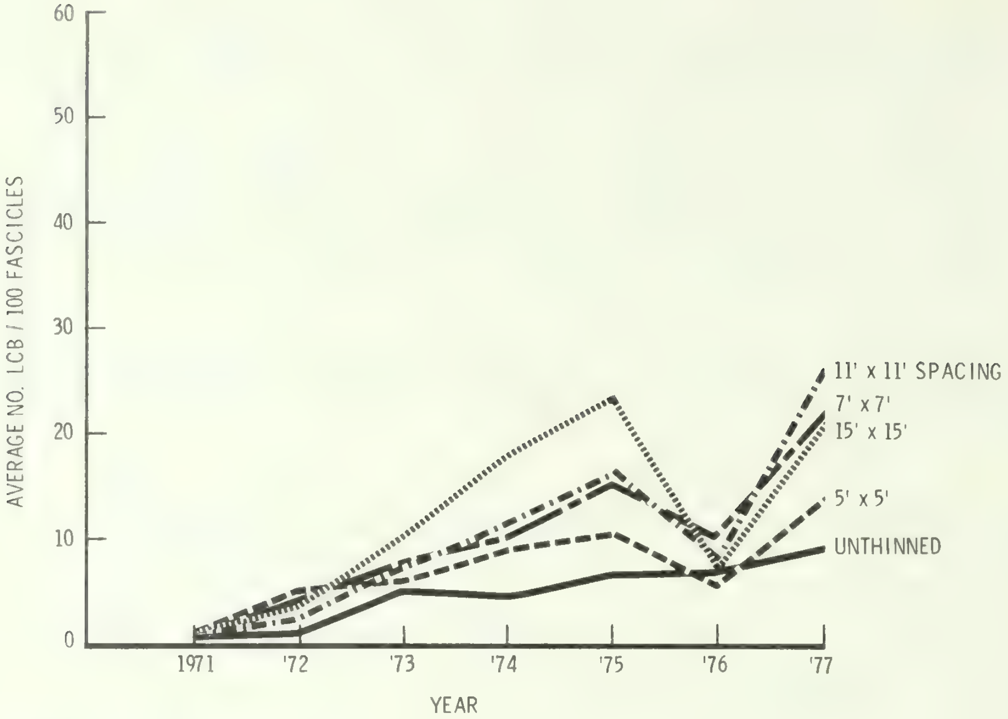


*Figure 9.--Larch casebearer spring-feeding populations, Coram Experimental Forest, Mont.*

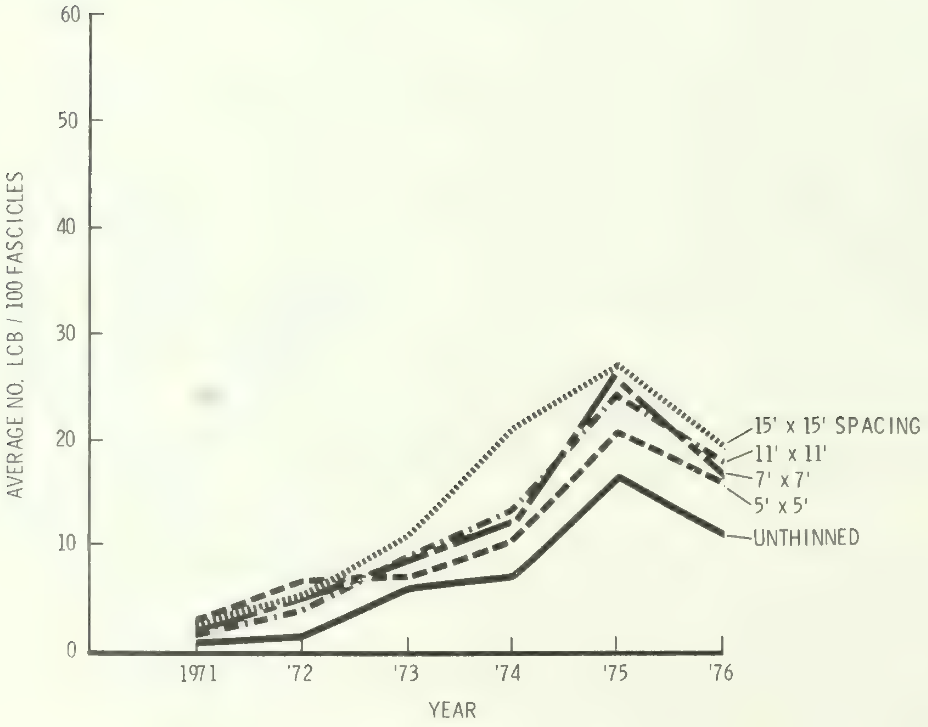


*Figure 10.--Larch casebearer pupal populations, Coram Experimental Forest, Mont.*

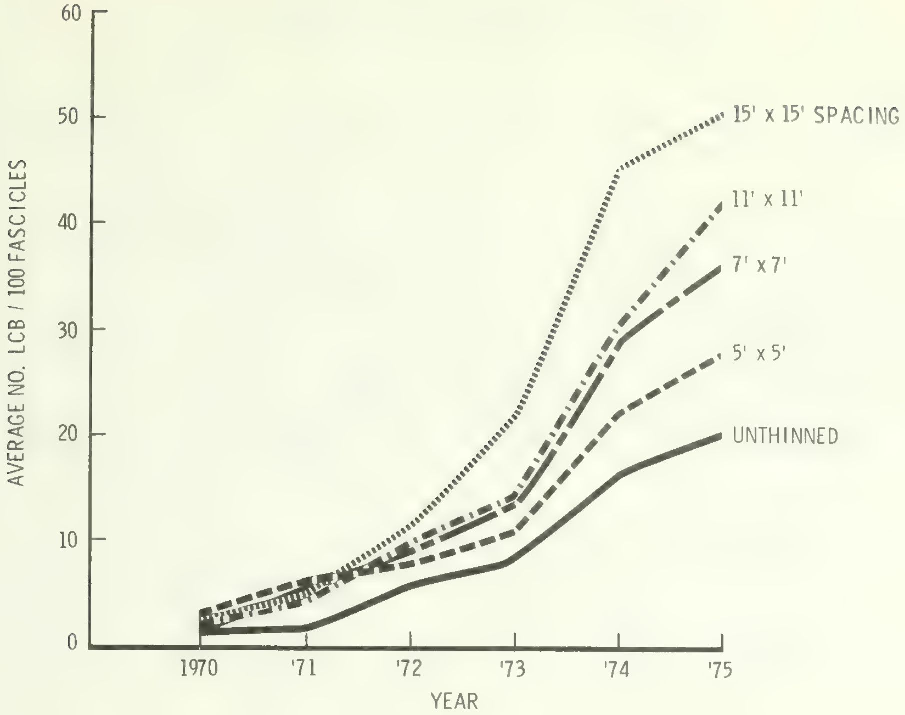


*Figure 11.--Larch casebearer fall-feeding populations, Coram Experimental Forest, Mont.*

Reproductive rates (population growth rates) between the five stocking densities ere computed for each of the three life stages using the regression model

$$Y = bX^2$$

here:

$Y$ = casebearer population density

$X$ = years

$b$ = reproductive rate.

th one exception, casebearer population densities increased more rapidly as the tocking density of western larch decreased from unthinned stands to 200 stems per cre (494 stems per ha).

Unfortunately, from a research standpoint, a cold-wet period in the spring of 1976 ontributed to a dramatic reduction in casebearer populations. Interestingly, this tural phenomenon reduced casebearer populations to essentially the same level on crop rees in the different stand densities (fig. 10). Apparently, the more exposed condi-ons of the widely spaced stands provided less protection from the cold-wet condition han did the denser stands. Although casebearer populations increased again in 1977, hey have not yet reached epidemic levels. Thus, it is not known if the increased growth f thinned western larch stands will be offset by defoliation caused by larger casebearer opulations in these stands.

# HOST TREE DAMAGE

Forest insect defoliators can be grouped into two classes according to the damage that results from their outbreaks. Those that attack nondeciduous conifers are the most damaging, primarily because these conifers cannot replace foliage once it is destroyed. A single complete stripping of foliage, or a number of consecutive losses of new growth can kill the host tree. Important examples in this group are the Douglas-fir tussock moth, *Orgyia pseudotsugata* McDunnough, and the western spruce budworm, *Choristoneura occidentalis* Freeman. Hardwoods and deciduous conifers can put out a second crop of foliage after defoliation, and they renew their foliage each spring. Therefore, they can survive more years of complete stripping. In the case of the larch casebearer, many western larch stands have withstood up to 10 years of severe defoliation without suffering direct tree mortality. However, these stands have suffered greatly reduced tree growth and decline in vigor. Other larch stands have suffered considerable tree mortality.

To date, the most serious consequence of the casebearer's invasion has been loss of tree growth. However, the utility-pole industry in Idaho has been adversely affected by prolonged casebearer defoliation. Industry has reported a serious reduction in the amount of sapwood in defoliated larch trees, thereby making these trees less desirable or even unfit for utility poles. Moreover, the decreased annual ring width tended to case harden larch poles during drying, thus preventing the penetration of preservatives into the wood.

Tunnock (1970) reported on casebearer populations and defoliation at elevations ranging from 2,000 to 5,000 ft (609 m to 1,524 m). His data suggest that above 4,000 ft (1,122 m) possibly only light casebearer populations can develop and they will not cause enough defoliation to affect radial increment of western larch. However, in other years (1964-1967), complete "browning" of larch caused by casebearer defoliation was observed from the valley bottom at Mullan, Idaho, (elevation 3,277 ft; 999 m) to the summit of Lookout Pass (elevation 4,728 ft; 1,441 m), bordering Idaho and Montana (personal observation).

In prolonged outbreaks, such as in the first 10 years from 1957 to 1967, some idea of the casebearer's destructive potential, as far as growth loss alone, is illustrated by the following calculation. These figures pertain to the Northern Region, and are considered conservative:

There are about 2.7 million acres (1.1 million ha) of commercial larch type in the Northern Region. At a growth rate for all species of 200 board feet per acre, we would expect 300 million board feet annual growth production for the total area. If one-half of the total volume is comprised of western larch, then 150 million board feet of larch should be produced annually. Studies have shown that after several years of severe casebearer infestation there has been from 75- to 95-percent reduction in annual growth, or from 112 million to 142 million board feet. At a stumpage value of $60.00 pe thousand board feet, the loss of growth alone could exceed $7 million annually.

## Nature of Damage

Damage results chiefly from the feeding of maturing fourth-instar larvae on the new foliage in the spring. Mined tips of the expanding needles appear whitish in early May, but in a few weeks they wither and turn brown. In severe infestations the foliage is destroyed as soon as it appears; as the needles dry out, the trees acquire a reddish-brown appearance as though scorched by fire. In most years, browning of the foliage is most conspicuous in early June (fig. 12).

Generally, needle mining begins within a week after the appearance of vegetative growth (usually about mid-April). If the weather is favorable and warm, fascicles of needles can be destroyed before they have a chance to expand and elongate (fig. 13); however, periods of cold wet weather favor the development of larch foliage by retarding casebearer feeding. If the needles are allowed to reach their full length, the amount of defoliation caused by a casebearer larva is significantly lessened.

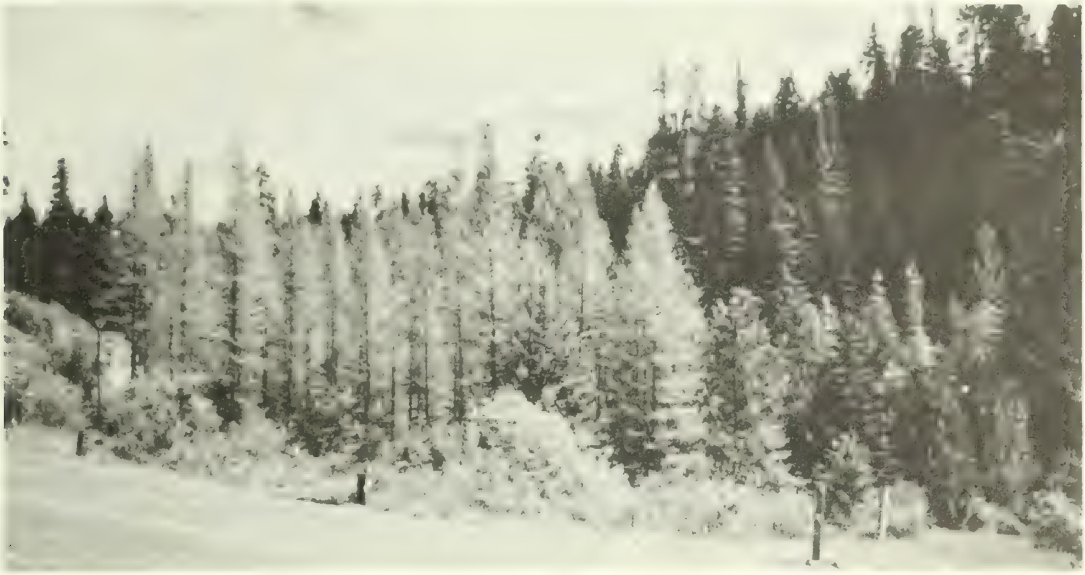


*Figure 12.--Stand of young western larch completely defoliated by larch casebearer near St. Maries, Idaho.*

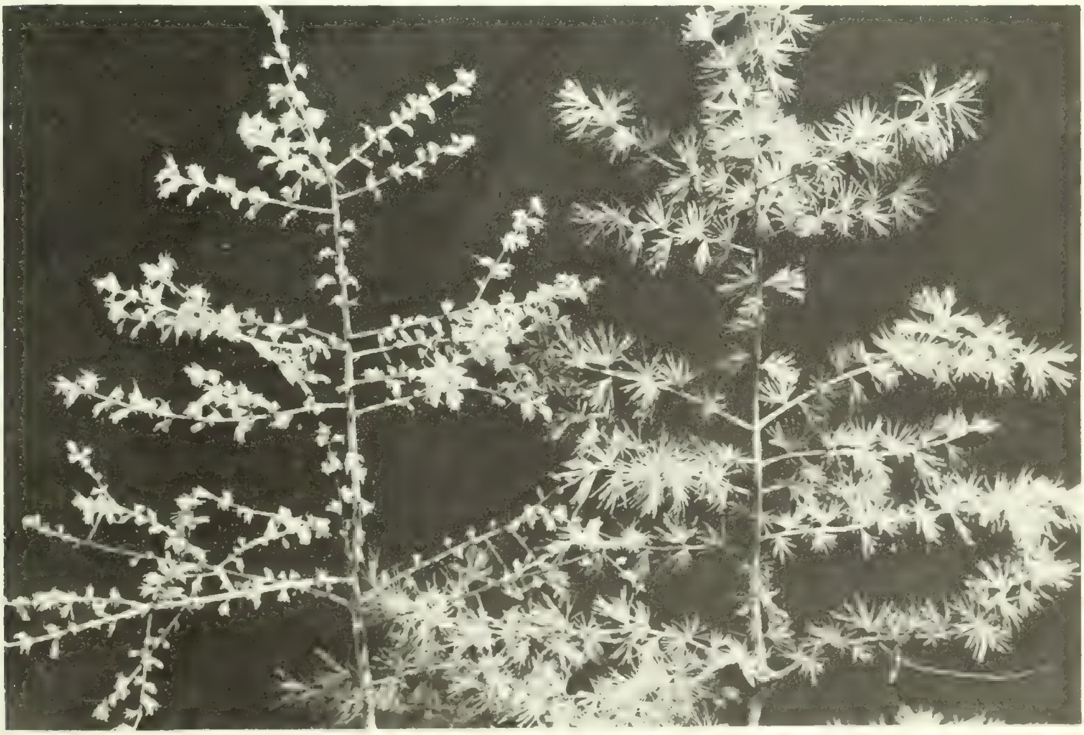


*Figure 13.--Two branches from western larch trees, comparing the normal appearance of undamaged foliage with complete destruction of needles caused by larch casebearer feeding.*

In severe infestations, and defoliation extends over a number of years, the needles become progressively shorter and a single larva requires more needles to complete its development. In one instance, after 4 years of heavy defoliation, needle length was reduced to less than one-half inch (1.27 cm)--compared with a normal length of about 1-1/2 inches (3.81 cm). Under these circumstances, one casebearer larva requires the equivalent of about two fascicles to complete its development. A count of 180 fascicles gave an average of 38 needles per fascicle for the first crop of foliage. Observations showed that when these needles were destroyed for more than half their length a second crop was produced in the middle of the fascicle, numbering fewer than half as many needles as the first crop--or 16 needles per fascicle. The second crop of needles was produced in time to receive the eggs of female moths (June 1). Otherwise, on heavily defoliated trees, egg laying would have been restricted to the newer needles produced on current year's growth tips that begin to elongate in early June.

While the casebearer is in the needle mining stage (instars I, II) from late June to mid-September, larch trees lose their brownish color and assume a green appearance because of the elongation of new shoots. In severe infestations, trees may again appear brownish in September because of defoliation by instar III larvae; however, because larch has completed its current year's growth by this date, the amount of damage by fall-feeding larvae is of less consequence than defoliation in the spring.

When casebearer populations are relatively light and foliage is plentiful, larvae feed indiscriminately upon the needles--often wandering considerably between feeding sites. Under these conditions a needle is usually mined only once. In a greenhouse experiment, 10 fourth-instar larvae were placed singly on each of 10 western larch seedlings to determine the amount of foliage necessary to complete their development.

The following tabulation shows the number of individual needles fed upon and the total amount of foliage consumed:

| *Larva No.* | *Total No. needles fed upon* | *Cumulative total needle length consumed (cm)* |
|---|---|---|
| 1 | 35 | 18.24 |
| 2 | 25 | 14.99 |
| 3 | 25 | 14.94 |
| 4 | 23 | 14.61 |
| 5 | 21 | 13.74 |
| 6 | 29 | 13.34 |
| 7 | 19 | 12.29 |
| 8 | 23 | 11.58 |
| 9 | 19 | 10.24 |
| 10 | 17 | 9.12 |
| Totals | 236 | 133.09 |
| $\bar{x}$ | 23.6 | 13.31 (5.24 inches) |

Thus, each larva fed upon an average of 23.6 ± 5.3 needles and consumed an average total needle length of 13.31 ± 2.64 centimeters before it pupated.

From a distance, needle discoloration of western larch caused by casebearer feeding can be confused with fungus diseases, particularly *Hypodermella laricis* Tubeuf (Leaphart and Denton 1961). In late May or early June, all needles infected by this fungus suddenly turn reddish brown, although needles apparently become infected soon after foliage growth starts. The casebearer will feed upon these needles until they begin to change color, so apparently it is unaffected by the fungus infection.

## Relationship of Casebearer Densities to Damage

The possibility of predicting potential defoliation by larch casebearer has several advantages. Counts of overwintering larvae can be used to forecast regional or forestwide population and damage trends, to select sites for field experiments of promising chemicals for casebearer control, and to select sites for release of introduced parasites.

Ciesla and Bousfield (1974) developed a quadratic regression model ($Y = 4.015 + 0.4419X - 0.001036X^2$) for forecasting defoliation potential by the casebearer. Based upon this model, they classified the intensity of feeding injury into four broad classes of damage as shown in the following tabulation:

| *No. overwintering larvae/100 spur shoots* | *Defoliation index* | *Predicted defoliation* |
|---|---|---|
| 0 - 11.5 | 0 - 8.9 | Negligible |
| 11.6- 60.4 | 9.0-26.9 | Light |
| 60.5-136.5 | 27.0-44.9 | Moderate |
| 136.6-236.75[1] | 45.0 | Heavy |

---

[1] Highest population density observed.

The authors point out that their model was based on only one variable, overwintering population density. Other variables such as elevation of the stand in question, parasites, predators, volume of foliage, age of infestation, and climatic factors that might occur after population counts are made, undoubtedly could influence levels of defoliation.

In a study to determine susceptiblity of western larch stands to varying intensities of casebearer populations and defoliation, a model was developed similar to the foregoing, but based upon casebearer pupal populations in a *Thuja plicata/Pachistima myrsinites* habitat type (Denton 1976).

Defoliation ratings ($Y$) and corresponding numbers of casebearer pupae per 100 fascicles ($X$) for individual trees were regressed and a quadratic regression model ($Y = 12.48 + 0.5241X - 0.00147X^2$) was computed to determine the relationship of casebearer populations and defoliation (fig. 14). Based upon the regression curve, the following categories of defoliation intensities were derived:

| *No. pupae/ 100 fascicles (X)* | *Defoliation index (Y)* | *Defoliation classification* |
|---|---|---|
| 0-10 | 0- 9 | Negligible |
| 11-30 | 10-27 | Light |
| 31-80 | 28-45 | Moderate |
| 81+ | 46-60 | Heavy |

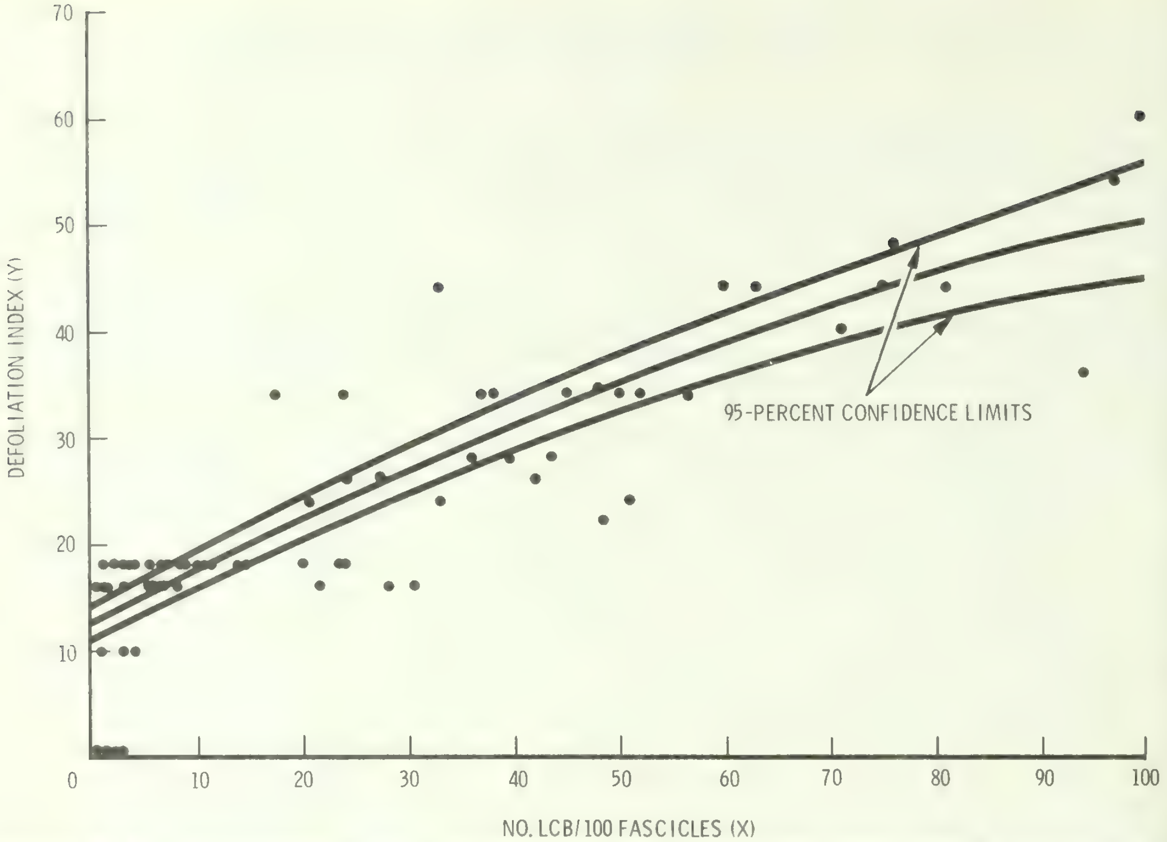


*Figure 14.--Defoliation index over density of larch casebearer pupal populations. Regression equation:* $Y = 12.48 + 0.5241 X - 0.00147 X^2$.

## Host Mortality

For the first 10 years following the casebearer's discovery, defoliation had not been known to kill western larch. However, branch dieback and greatly reduced needle length became pronounced after 5 or 6 years of heavy defoliation. In 1967, dead and dying trees were reported on the former St. Joe National Forest (now the Idaho Panhandle National Forests). Aerial surveys in 1968 revealed serious tree deterioration within thousands of acres of western larch in northern Idaho. In that year, a study was conducted to determine the extent that larch casebearer and other factors contributed to the deterioration of these larch stands (Tunnock and others 1969). Jung (1942) and others cite instances of direct tree mortality in Europe following casebearer outbreaks. However, in the East, Webb's (1953) studies suggest that although the casebearer may contribute to host tree mortality, it is seldom wholly responsible.

In 1968, annual radial growth had decreased to 0.1 mm in many trees compared to more than 3 mm prior to the casebearer's invasion (fig. 15 and 16). This amounted to a 97 percent growth reduction in a 5-year period. Beetles were found in 11 of the 72 trees sampled. Western larch borer (*Tetropium velutinum* LeConte) was collected from nine trees and scavenger beetles from the other two (Appendix tables 1 and 2). The borer was abundant enough in only six trees to be a factor in causing mortality. Root rot (*Armillaria mellea* (Vahl.) Quel.) was detected in 14 of the 72 trees and could have contributed to the death of several. Tree deterioration showed no correlation with soil series or fertility. This study did not confirm that larch casebearer was the sole cause of tree mortality; however, the casebearer was definitely responsible for weakening and predisposing western larch stands to mortality.

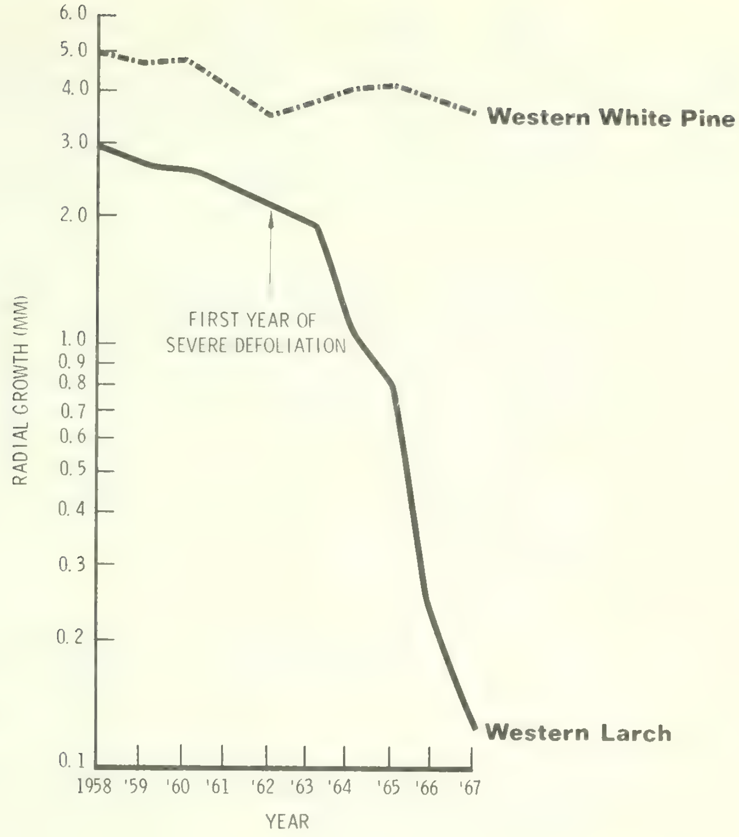


*Figure 15.--A comparison of radial growth increments of defoliated western larch and western white pine from Marble Creek, Idaho.*

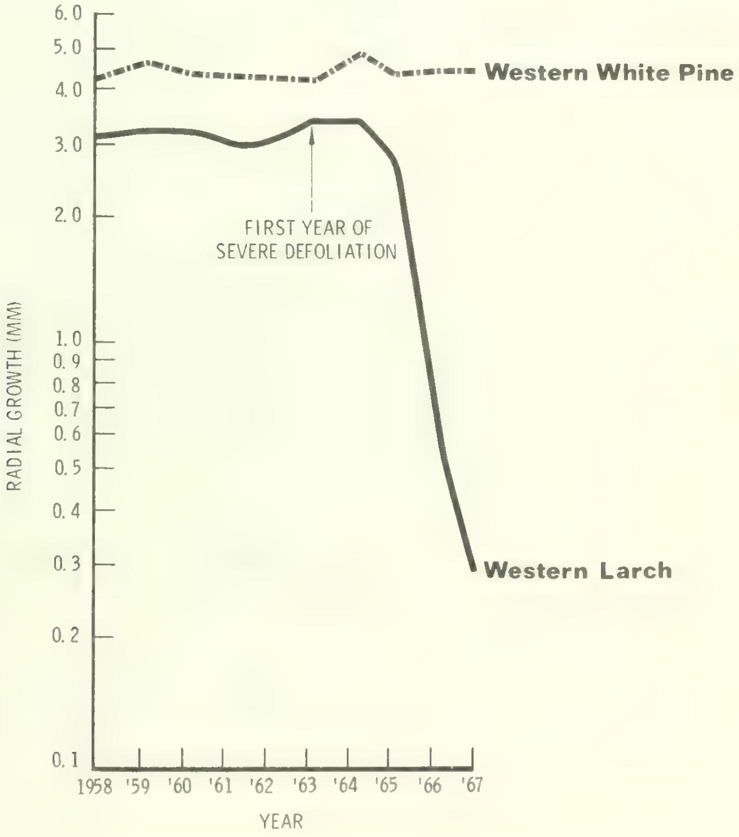


*Figure 16.--A comparison of radial growth increments of defoliated western larch and western white pine species at Falls, Idaho.*

In following years, indirect tree mortality caused by casebearer defoliation was apparent in a number of stands. Larch is a seral species exhibiting a high degree of shade intolerance, and it can survive only if it maintains a dominant position in the tree canopy. Repeated defoliation slows larch growth and places it in a competitive disadvantage with its associated species. In this way, larch loses its dominance in the stand and eventually its potential for recovery, even though the outbreak may subside later.

The foregoing phenomenon occurred in northern Idaho. In a plot at Falls, Idaho, the casebearer population was greatly reduced by a drought in 1967, after western larch had sustained severe defoliation for 7 years. During this period, intermediate and suppressed larch trees lost their dominance to grand fir, *Abies grandis* (Dougl.) Lindl., and western white pine, *Pinus monticola* Dougl. By 1974, nearly all of the intermediate and suppressed larch had died--only dominant and codominant larch trees survived.

No direct larch mortality caused by casebearer defoliation has occurred since 1967 because of another drought in 1973 that again reduced casebearer populations before they could kill trees. Thus, the total impact of the casebearer's invasion of western larch forests remains to be determined.

# BIOLOGICAL CONTROL

In the East, at least 50 native parasite species and two introduced species are known to attack the larch casebearer (Webb 1953). One of the first questions was whether any biocontrol agents accompanied its introduction into Idaho. Laboratory rearings of casebearer pupae were begun in May 1958 to identify parasites attacking the casebearer in the West. Four thousand pupae were collected in two of the most heavily infested areas near St. Maries and reared in glass vials. The results are summarized in the following tabulation:

| *Collection location* | *No. casebearer moths emerged* | *No. parasites emerged* | *Percent parasitism* |
|---|---|---|---|
| Thorn Creek | 1,847 | 18 | 0.9 |
| Rocky Point | 1,801 | 86 | 4.5 |

Three species of native hymenopterous parasites were recovered, but only one in any abundance. Three specimens of the braconid *Bracon pygmaeus* Prov. emerged and one specimen of an ichneumonid, *Pristomerus* sp. The remaining 100 parasites were the chalcid *Spilochalcis albifrons* (Walsh). As will be shown later, through the years increasing numbers of native species of parasites are finding the casebearer an attractive host.

## Original Exotic Parasite Introduction

In 1960, a program was started to import exotic parasites of the casebearer into Idaho. The primary candidate was *Agathis pumila* (Ratz.). This European braconid was introduced during the 1930's into Eastern United States and Canada and is credited with materially helping to check and control casebearer infestations there (Turnbull and Chant 1961). The casebearer is its sole host, and it is abundant in the Northeast.

Entomologists at the Northeastern Forest Experiment Station's former Forest Insect Laboratory at New Haven, Conn., reared several thousand *A. pumila* adults from casebearers collected in Rhode Island. Five shipments of parasites having nearly a 1:1 sex ratio were received on successive days beginning on June 23, 1960, and released at five locations within a 30-mile (48.3 km) radius of St. Maries, Idaho (table 2). Additional releases were planned for several years; however, in 1961, the casebearer declined to such low levels in the East that it was not economically feasible to collect *A. pumila* there again until 1964.

Table 2.--*Numbers of* A. pumila *released in the vicinity of St. Maries, Idaho, during June 1960*

| Shipment No. | Number shipped | Percent mortality in transit | Number released | Location |
|---|---|---|---|---|
| 1 | 1,025 | 70 | 305 | Thorn Creek |
| 2 | 500 | 7 | 464 | Thorn Creek |
| 3 | 500 | 19 | 404 | Rocky Point |
| 4 | 500 | 16 | 419 | St. Joe City |
| 5 | 1,000 | 23 | 372 | Indian Canyon |
|  |  |  | 396 | Calder |
| Totals | 3,525 |  | 2,360 |  |

In 1962, several specimens of *A. pumila* were recovered from mass rearings of casebearer collected at Thorn Creek, Rocky Point, and Indian Canyon. These recoveries showed that the parasite had gone through two generations and apparently was becoming established in Idaho. Since then the rate of parasitism has been determined every 2 years until 1972. Although *A. pumila* has been recovered in all five release locations, significant buildup has occurred after 12 years in only three of these areas (table 3). As of now, there is no explanation why parasite populations did not increase during the first 10 years at Thorn Creek or Calder; however, in 1972, there were indications of increasing parasitism in these areas (table 3).

The potential effectiveness of *A. pumila* in suppressing the casebearer was shown in the Indian Canyon area where 372 parasites (of which 200 were females) were released in a relatively isolated larch stand in 1960. In that year, the overwintered casebearer population averaged 278 larvae per 100 fascicles. In the following 8 years, parasitism increased to 68 percent (table 3) and the overwintered casebearer larvae averaged less than 20 per 100 fascicles. This shows that *A. pumila* is not only effective in reducing casebearer populations, but also can maintain a high level of parasitism even at low host densities.

Table 3.--*Parasitism of larch casebearer by* A. pumila *released in the vicinity of St. Maries, Idaho, during June 1960*[1]

| Location | Year |  |  |  |  |
|---|---|---|---|---|---|
|  | 1964 | 1966 | 1968 | 1970 | 1972 |
|  | *Percent* |  |  |  |  |
| Thorn Creek | 0 | 1 | 0 | 2 | 7 |
| Rocky Point | 12 | 15 | 46 | 48 | 38 |
| St. Joe City | 14 | 46 | 48 | 42 | 50 |
| Indian Canyon | 10 | 16 | 68 | 66 | 43 |
| Calder | -- | 2 | 0 | 1 | 14 |

[1] A few specimens were reared in 1962 from Thorn Creek, Rocky Point, and Indian Canyon.

## Large Scale Rearings, Propagations, and Distributions of *Agathis pumila*

### 1964

In 1964, the Northern Region and the Intermountain Forest and Range Experiment Station began a program to import large numbers of *A. pumila*-parasitized overwintered casebearers from the East for rearing and propagation in Idaho (Terrell and Denton 1965). The purpose of the program was to establish large colonies of *A. pumila* from which the parasite could be distributed throughout the casebearer infestation in western larch forests.

Samples of dormant casebearers were collected in March from 11 infestations in Maine, Vermont, and New Hampshire and sent to Missoula, Mont., to determine the amount of *A. pumila* parasitism by dissection. Although the parasite was common in all locations, it reached a high of 78 percent at Rutland, Vt. Therefore, a large collection of casebearer-infested tamarack twigs was shipped to Idaho from this area.

*Parasite rearings and releases.*--Late in March about 150 small, dormant larch trees were taken from a casebearer-free area near Missoula, Mont., and transplanted at Sandpoint, Idaho. The trees were planted in three squares over which 10x12 ft (3.05x 3.66 m) cages were erected. The cages were covered with 32-mesh Saran screen (fig. 17). On April 8, the infested larch twigs were fastened with hog rings to the limbs of the transplanted larch in small bundles (fig. 18).

The three cages were protected from rain and sun by placing tent flies over the top. Parasites were reared under quarantine conditions by providing double door entrances, covered on all sides with black plastic (fig. 17).

Soon after the larch foliage growth started in mid-April, the imported casebearer larvae broke hibernation and migrated from the larch twigs to feed on the western larch foliage. On June 8 casebearer moths began to emerge in the cages. Moths increased in numbers until a peak was reached near the end of June. These moths were killed daily to eliminate debris from accumulating on the screens.

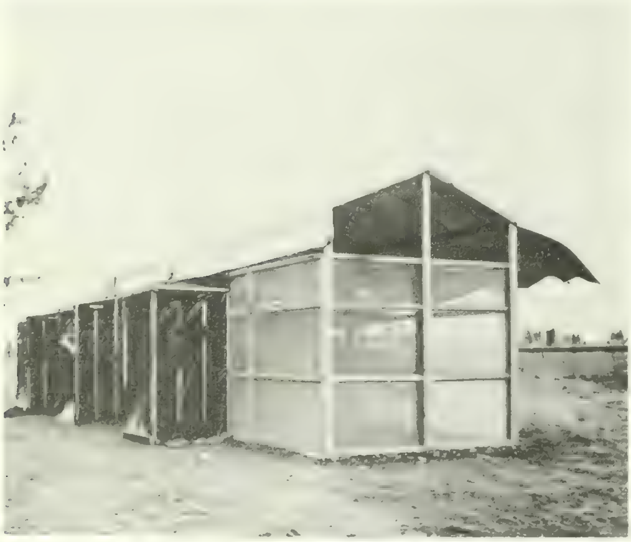


*Figure 17.--Three separate cages with light-trap entrances used to rear* Agathis pumila, *1964.*

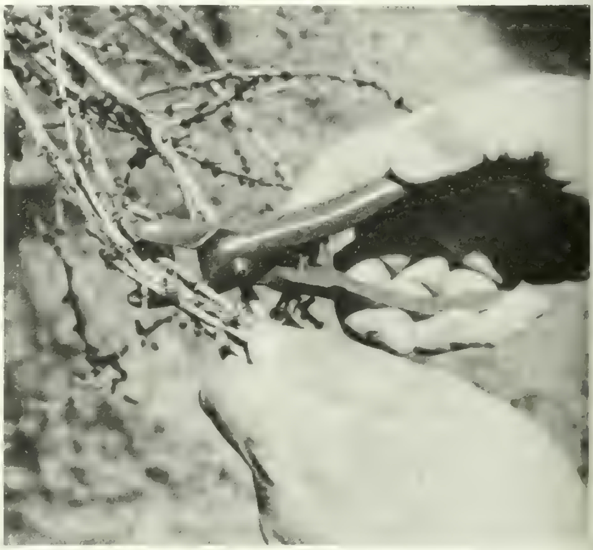


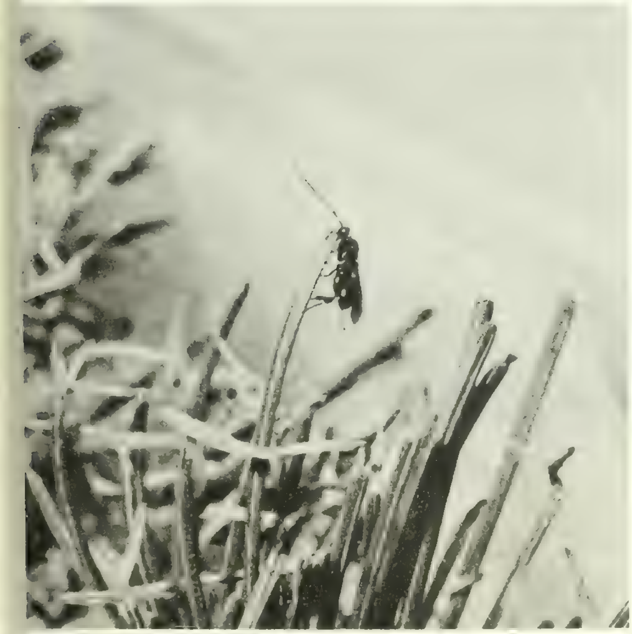
*Figure 18.--Attaching the imported larch casebearer-infested tamarack twigs to western larch trees in the rearing cages.*

On June 30, the first *A. pumila* emerged. Subsequent daily collections of parasites and their sex ratios are given in Appendix table 3. The first 1,000 parasites were nearly all males--12 days elapsed before males and females emerged in equal numbers. From then on, females outnumbered males in increasing numbers. A total of 10,033 *A. pumila* was collected in 1964. The sex ratio was 1 male to 1.3 females.

*Collecting parasites.*--*A. pumila* is a small, delicate hymenopterous insect about 2 mm long--less than half the size of a mosquito (fig. 19). They are phototropic, and shortly after emerging they fly toward the brightest part of the cage. They are most active at temperatures above 70°F (21.1°C); therefore, the best period for collecting was from 10:00 a.m. to 4:00 p.m.

Several types of aspirators were made in anticipation of problems in collecting these fragile insects. A vacuum generator developed to handle small machine parts in assembling delicate instruments proved to be the only one usable that caused the least injury to the parasites (fig. 20). The vacuum could be regulated to any degree. Air was drawn through a hypodermic needle by a small electric motor-driven pump. A 25-gage needle was the best size. The end of the needle was cut off square and polished to remove sharp edges. The amount of vacuum was controlled at the motor; on and off vacuum was controlled by covering or uncovering a vent near the collecting needle with the index finger.

A technique for using this apparatus was developed: As the parasite rested on the screen, the end of the collecting needle was brought toward the head from the front in a sweeping motion. The slight vacuum was sufficient to pull the insect to it for a distance of about 1 mm. Less injury resulted and the insect could be released quickly because it was usually caught by the head or thorax rather than by the legs. If the legs were caught, they were sometimes drawn into the needle--release was not only delayed but there was also a chance of injury in trying to free the insect. Parasites were held briefly on the needle to determine the sex; *A. pumila* females have a prominent ovipositor.



*igure 19.--Female* Agathis pumila *preparing to oviposit on a larch casebearer larva mining inside of a western larch needle.*

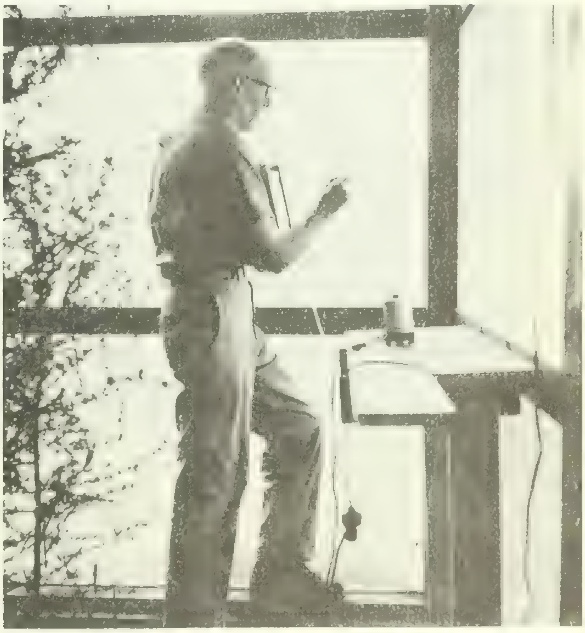


*Figure 20.--Vacuum generator used to collect* Agathis pumila.

*Agathis pumila* adults are not easily disturbed and thus are easy to handle. They have a characteristic appearance and movement that is soon recognized. On the screen their movements could be described as ant-like, with the antennae in constant motion. At the peak of emergence one man with a vacuum generator could collect about 400 parasites per hour. The best method was to collect the parasites and place them directly into holding boxes. These boxes were 4x6x11 inches (10.16x15.24x27.94 cm) and fitted with a sliding glass cover to release the parasites in the field. In one end of the box a section of 2-1/2-inch (6.35 cm) mailing tube with a screw cover was inserted; in the opposite end a Saran screen cylinder with the inner end closed was inserted into the box to serve as a feeding site (fig. 21).

To collect the parasites, the screw cap was removed from the mailing tube and the opening was covered with black plastic. A V-shaped flap was cut in the plastic cover. This flap was held open by a piece of tape when collecting and closed with tape at other times. The captured parasites were inserted through the opening and freed by releasing the vacuum. Usually 100 parasites were placed in a box.

*Holding the parasites.*--Various methods were tried for storing the parasites during the early phase of emergence. As shown in Appendix table 3, about 1,000 male *A. pumila* emerged during the first 8 days and only a few females. Later, females outnumbered males at an increasing ratio. It was desirable to hold the early emerging males to balance out the later emerging females.

Small numbers of parasites were put into holding boxes described above and stored at 40°F (4.4°C) in a household refrigerator. Most of them died within a few days.

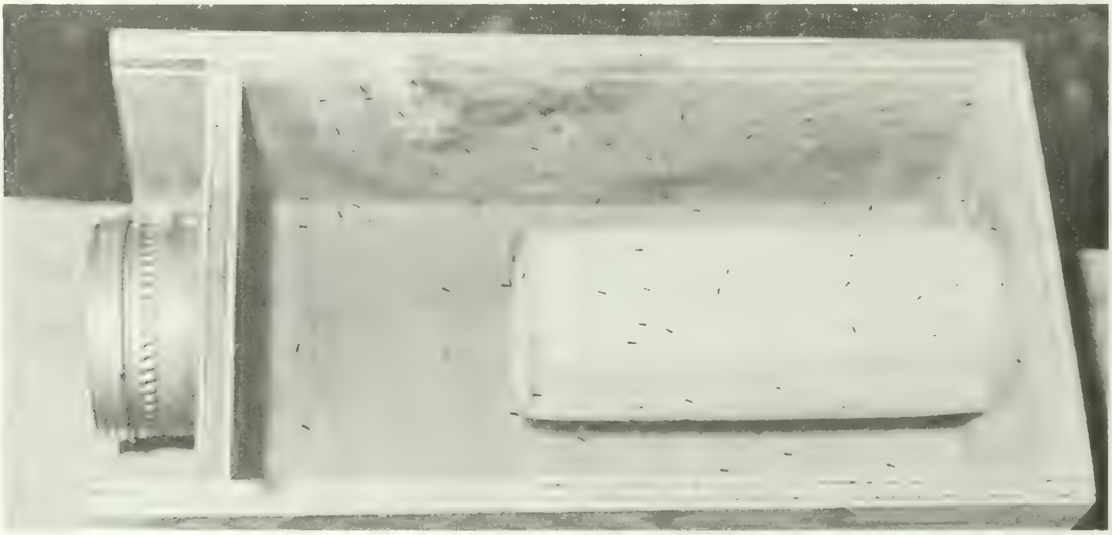


*Figure 21.--Boxes with sliding glass covers used to collect and hold* Agathis pumila.

One thousand were put into a 16x16x24-inch (40.64x40.64x60.96 cm) Saran screen cage; 700 died within 24 hours. Later observations indicated that Saran screen newly off the roll exudes a volatile substance that is toxic to these parasites. This problem was solved by scrubbing the screen with warm, soapy water.

Although more needs to be learned about keeping these insects in storage, apparently they can be held for about 10 days. They should have a roomy cage of well-cleaned or weathered screen. Fresh larch foliage should be placed inside, treated as described in the following section. The cage should be kept in a cool, humid place such as on damp, shaded ground. Placing moistened burlap over the cages helped maintain humidity.

Except for holding the excess males that emerged first, there was no need to keep these insects caged more than 24 hours. Generally, collections were completed in late afternoon and the parasites were held overnight and released the following forenoon.

*Feeding the parasites.*--Newly emerged adult *A. pumila* need food and water. Under natural development, they may feed on nectar or aphid honeydew. Honey is the recommended substitute for natural food. Honey also has the advantage of absorbing about 18 percent water under humid conditions; therefore, it provides both food and water. Undiluted honey entangled the parasites when brushed on the screens of the holding boxes. The best method found was to dilute 1 part honey in 16 parts distilled water. This was first fed from sponges inserted into the screen tubes. A better technique was to dip sprigs of fresh larch foliage into the diluted honey-water solution, shake them nearly dry, and place them in the holding boxes.

A very thin film of honey remained on the foliage that did not entangle the insects. They fed avidly on this residue and the foliage provided a perching site. A small piece of dampened sponge was also placed into each cage to provide moisture. Without this added moisture, considerable mortality occurred.

*A. pumila releases.*--The objective of this project was to propagate local colonies of parasites for distribution throughout the casebearer infestation. Nine small trees and 14 limbs were caged for this purpose (fig. 22). Free liberations were made in three locations. Moderate infestations were sought because heavy infestations are so overpopulated with casebearers that considerable natural mortality by starvation is suspected. Parasites introduced into these high populations might suffer the same mortality as their host larvae.

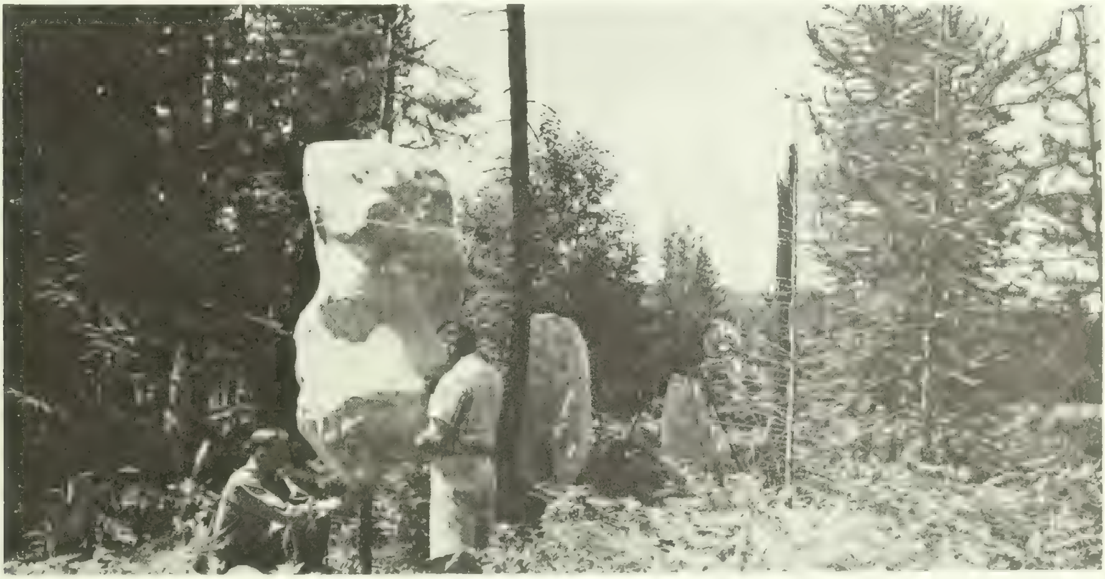


*Figure 22.--Caging small western larch trees to propagate local colonies of* Agathis pumila, *1964.*

Casebearer populations were estimated by counting eggs per foliated fascicle and multiplying by the estimated fascicles per limb or tree. These were rather rough estimates but served a later purpose of determining the number of female parasites to release in each cage. Not more than one female per 200 eggs was released. Each female can parasitize about 60 to 80 casebearers. The plan was to have more than enough casebearer larvae for each female parasite so that she would not have to search long to locate her hosts.

The numbers of parasites released and the results obtained in the caged liberations are given in Appendix table 4. Of the 10,033 *A. pumila* reared, 5,200 were released on caged trees and limbs, 3,216 were freed in open liberations in three separate areas, and about 1,300 died. In addition, about 300 were caged for biology studies. Of those that died, more than half were males lost during early attempts to hold them for later emerging females. After female emergence was such that there was no need for prolonged holding, only 6.4 percent of the parasites died before release. Most of this mortality probably resulted from collecting injury.

The great reduction in casebearer numbers from eggs to hatched larvae (Appendix table 4) was a surprising development. Only about 10 percent of the eggs hatched. Although the percentage of parasitism in the caged liberations was gratifying, the reduction of casebearer population reduced the number of parasites that might otherwise have been recovered from this source. Percent parasitism was determined by dissecting 25 casebearer larvae from each cage in December.

Very high mortality of parasites occurred in the four Saran screen sleeve cages. Dead parasites were numerous within 24 hours. In one instance, dead and dying parasites were noted immediately after they were released into the cage. After the screen had weathered for several days, it appeared to be safe.

*Sanitizing the cages.*--The rearing was terminated when the emergence of *A. pumila* decreased to only a few per day. The transplanted larch trees were cut at ground level and the material was piled in the centers of the cages. The cages were then sprayed on the inside with a strong solution of malathion and the piles of debris were sprayed to saturation with diesel oil. The piles were burned after the cages were lifted off the foundations and moved aside.

## 1965

In 1965, procedures similar to those of 1964 were utilized to determine a source of *A. pumila* in the East. A sample from Windsor, Mass., with 66 percent parasitism, gave the highest percentage of *A. pumila* and was selected for importation of this parasite. Six large burlap sacks of infested tamarack twigs were shipped to Sandpoint, Idaho, in early April (Terrell and Denton 1966).

*Rearing the parasites.*--The rearing cage at Sandpoint was enlarged to 10x60 ft (3.05x18.30 m) (fig. 23). About 235 small (up to 6 ft; 1.83 m) western larch trees were transplanted into the cage in March and early April. In mid-April the Windsor twigs were placed on the trees.

To prepare for propagating the parasites, 45 open-grown western larch trees from 8 to 26 ft (2.44 to 7.93 m) tall, in a plot 10 mi (16.1 km) north of Priest River, Idaho, were covered with fine-mesh cheesecloth cages (fig. 24). The cages were made by sewing the edges of three 50-yard (45.7 m) bolts of cloth together to form a tube. The material was 38 inches (96.52 cm) wide, which gave a sleeve about 10 ft (3.05 m) in circumference by 50 yd (45.7 m) long. About 350 yards (319.9 m) of sleeve cages were used.

The first parasites emerged July 2, only 2 days later than in 1964. A thousand males emerged during the first 6 days before the first female emerged. Sixteen days passed before males and females emerged in equal numbers. By that time, 11,400 males and 2,700 females had emerged. Females then emerged in increasing numbers and the ratio of males to females decreased until there was only about 1 male to 10 females during the last half of the emergence. A total of 29,340 *A. pumila* was recovered during the period July 2 to August 31 (Appendix table 5). The sex ratio was 1.2 males to 1 female.

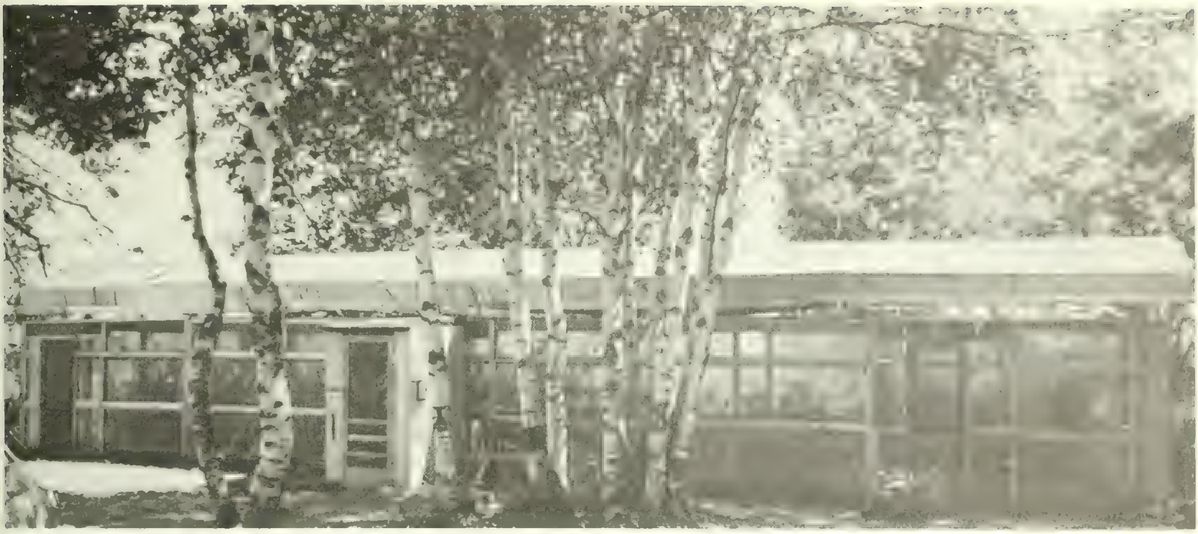


*Figure 23.--The large screened cage used to rear* Agathis pumila *in 1965. Only the single light-trap entrance in the center was used.*

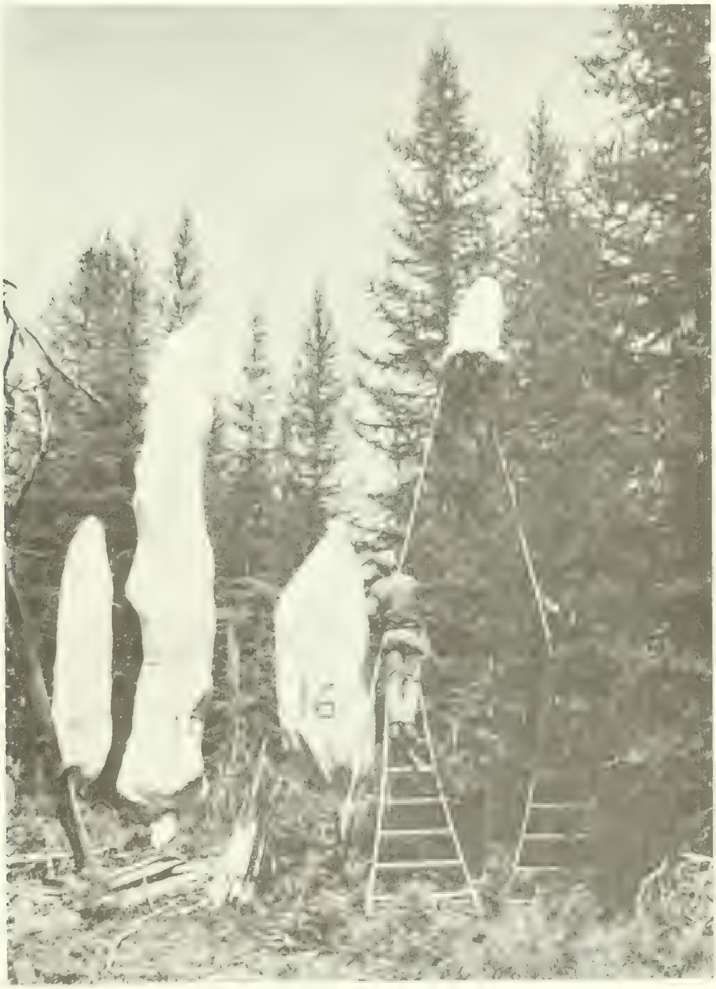


*Figure 24.--Caging western larch trees to propagate* Agathis pumila, *1965.*

The high ratio of males to females during the initial emergence period was anticipated from experience in 1964. As in 1964, the males were collected and held in screen cages for later use when a disproportionate number of females would emerge. Although held under cool, high humidity, 5,000 males died when held for a 12-day period.

*[illegible] A. pumila on western larch trees.*--The 45 trees caged to receive the emerging parasites were of different heights, crown densities, and casebearer numbers. These factors were used to develop a population index for each tree. The number of parasites introduced into the cages was determined by this index.

Approximately 12,000 females were released onto the caged trees. The first batches had an equal or greater number of males than females; later batches often had no more than 1 male to 8 or 9 females, but many of these later plantings were put into cages already partially stocked. Some cages were planted with up to four separate batches of parasites at different intervals.

When a batch of parasites was ready for release, a slit was cut along a seam of the cage, the holding box was inserted, and the glass cover removed (fig. 25). During cool weather, the parasites were not active and the open boxes were often hung from a limb inside the cage to be retrieved later. When it was warm, the parasites readily left the box. The slit was then sewed shut. The cheesecloth cages were removed from the trees in late August when it was presumed that the parasites had finished ovipositin

During the rearing and collecting of parasites from the rearing cage, it was observed that *A. pumila* would start emerging about 10:00 a.m. when the temperature reached about 70°F (21.1°C). Emergence diminished by 3:00 p.m., and usually ceased by 5:00 p.m.

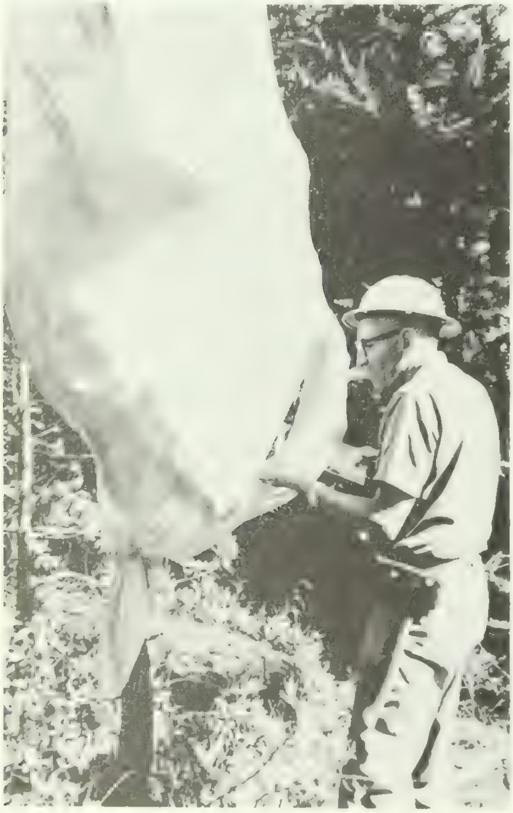


*Figure 25.--Releasing* Agathis pumila *onto caged western larch trees, 1965.*

As in 1964, the parasites were collected from the cage screen by a vacuum generator and released directly into the holding boxes. These boxes were modified from those used in 1964. The backs were cut out of the boxes and the openings covered with Saran screen. Several layers of burlap were made into a pad and fastened to the screen. The burlap pads were sprayed with water occasionally while the parasites were being collected. The cool, moist environment kept the parasites quiet.

Sprigs of larch foliage dipped into a solution of 1 part honey and 16 parts water were placed in the boxes before the parasites were put in. Usually, about 400 parasites could be collected into one of these boxes.

After collecting, the boxes were put into a cupboard made of framework covered with several layers of burlap; this was also kept wet. In 1964, some parasites always died in boxes held overnight. In 1965, there was practically no mortality in collections of parasites held 24 hours in the cool, 100-percent-humid environment. *A. pumila* could be kept alive and vigorous for about a week by this method. In actual practice, they were seldom held more than 24 hours once females emerged in sufficient numbers.

The sprigs of larch foliage placed in the boxes usually had hatched casebearer larvae in the needles. Female parasites readily attacked the casebearer larvae and oviposited through the epidermal layer of the needle. The female always pierced the needle on the side opposite the casebearer egg.

*Estimating the parasitized casebearers.*--When *A. pumila* parasitizes a casebearer larva, the first-instar parasite is soon found inside the casebearer. It remains an internal parasite in the living larva throughout the winter and can be found at any time by dissecting the casebearer larva under a binocular microscope.

To estimate the progeny of the parasites caged on the 45 trees, overwintering casebearer larvae were collected during December and dissected. However, to estimate the number of parasites on all the trees, the casebearer population had to be estimated. The dormant casebearer larvae were attached to the spur shoots and twigs.

The problem was approached by measuring the total length of the caged boles on the 45 trees less the top 2 ft (0.61 m). The top 2 ft (0.61 m) were eliminated because the limbs were short and had been compacted by the top of the cages. The cumulative total length of crown was 581 ft (177.21 m).

Ninety random samples consisting of 1 ft (0.305 m) were taken in the 581 ft (177.21 m). All the limbs in each sample were counted and two, the lowermost and the uppermost, were cut from each tree and brought into the laboratory. All the casebearers on these 180 limbs were counted. There were 53,360 of them. Thus, it was estimated that the total number of casebearers on the 45 trees (6,065 ± 244 branches) was 1,807,370 ± 157,690.

Twenty casebearer larvae, 10 from each of the paired limbs, were dissected. The casebearer population was estimated for each sample foot and the percent parasitism for each foot was applied to the sample. Parasite progeny per foot (0.305 m) was 447.8 ± 82.6. Thus, the number of *A. pumila* on the 45 trees was estimated at 260,000 ± 48,000.

The estimated number of overwintering parasites represented an increase of about 12 to 1. While this is not a large increase, it was considered satisfactory considering the artificial rearing conditions and the low ratio of males to females in half the batches caged. It appeared that the average female parasitized 22 casebearers, considerably less than her biotic potential of about 60 to 80 per female.

## 1966

In March and early April, all the limbs on the 45 trees were removed. The 90 1-ft (0.305 m) samples gave a close estimate of the total number of limbs--6,065 ± 244. The limbs were mixed to some extent and tied into units of 115. There were 52 units, each estimated to contain 5,000 *A. pumila.*

The units were distributed as follows:

| *No. units* | *Allocation* | *Estimated No. parasites* |
|---|---|---|
| 5 | Redistributed in rearing area | 25,000 |
| 9 | To Region 6 for planting in eastern Washington | 45,000 |
| 3 | Colville and Kaniksu National forests in eastern Washington | 15,000 |
| 25 | Distributed in Idaho | 125,000 |
| 10 | Distributed in Montana | 50,000 |
| 52 | | 260,000 |

Each liberation plot was mapped and marked to permit investigators to determine the establishment and buildup of *A. pumila* in future years. The release plots consisted of three to five open-grown larch trees, moderately infested by the casebearer where possible. The limbs were placed as high as possible in the branches of the plot trees, using 10-ft (3.05 m) orchard ladders (fig. 26). Large, branched limbs were simply intertwined in the branches of the plot trees. Small limbs and twigs were fastened to the branches with hog rings. When foliation started, the parasitized casebearer larvae broke hibernation and moved to the new foliage to feed and complete their development.

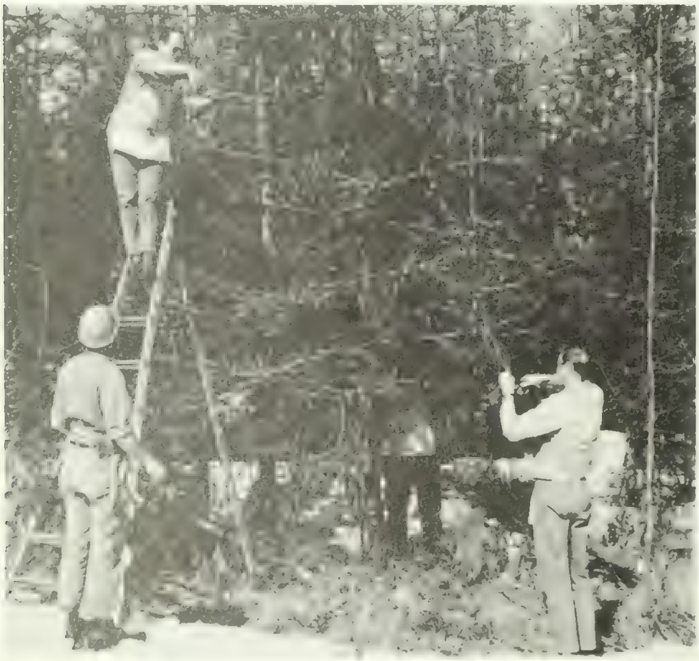


*Figure 26.--Distributing* Agathis pumila *throughout the larch casebearer infestation by attaching bundles of twigs containing parasitized casebearer larvae to western larch trees.*

Heavy casebearer infestations suffer considerable larval mortality from competition during the spring feeding period. For this reason, it was not desirable to plant thousands of additional parasitized larvae in heavy infestations; however, in many areas there was no alternative. This may have contributed to delayed or nonestablishment of *A. pumila* in some plots.

## 1967-1977

Similar procedures to those of 1966 were employed for the following 3 years in distributing *A. pumila* throughout the casebearer infestation in Montana, Idaho, eastern Washington, and British Columbia. One plot near Noxon Rapids Dam, Mont., where *A. pumila* was well established, was used as a source of parasites. The rapid increase of *A. pumila* in this area was remarkable. In 1964, 877 parasite adults were released and 400 adults in 1965; 80 percent of these were females. In 1967, dissections showed that 36.6 ± 2.2 percent of the casebearer population was parasitized.

Some realization of the possible number of parasites in the Noxon plot was gained by applying the above percentage to the casebearer population. An average casebearer infestation such as that in the Noxon plot may have as many as 50 million casebearer larvae per acre. Forty percent parasitism would indicate 20 million parasites.

By 1969, *A. pumila* had been distributed in 318 locations in Montana and Idaho, 59 in northeastern Washington, and two in British Columbia. Except for later releases on six Intermountain Station research plots in Idaho, no additional distributions were made in the Northern Region, but *A. pumila* adults were released in Oregon in 1971. All of he above release locations are well documented in a report by Bousfield and others (1974).

From 1975 through 1977, Boise Cascade Corporation distributed *A. pumila* on nine additional locations in larch forests of their ownership near LaGrande, Oreg.

## Success of *A. pumila* Distributions

In the early years, the overall effectiveness of *A. pumila* was limited by its failre to spread throughout the range of larch casebearer. Following release of *A. pumila* dults near Noxon Rapids Dam in 1964 and 1965, parasitism increased in a few years to 0 percent of the casebearer population within a quarter-mile (0.40 km) radius of the elease location. Beyond that parasitism began to decrease; this decrease became abrupt eyond a half-mile (0.80 km) radius. It was speculated that the lack of dispersal ould be attributed to the excessively large numbers of larch casebearers that were mmediately available to the parasite. The validity of this speculation was shown folowing a drought in 1967 that greatly reduced casebearer numbers in Idaho. Within a ew years, in one instance *A. pumila* was recovered in abundance (48 percent parasitism) bout 10 miles (16.1 km) distant from the release point.

Attempts are being made by Northern Region and Intermountain Station entomologists o determine the establishment of *A. pumila* in all of the locations where it was eleased or distributed in Idaho and Montana. Results thus far are given in the folowing tabulation:

| | *Idaho* | *Montana* |
|---|---|---|
| No. of release locations | 106 | 217 |
| No. of locations sampled | 103 | 105 |
| No. of locations with *A. pumila* | 73 | 55 |
| Percentage of locations with *A. pumila* | 71 | 52 |

Following a severe drought in Idaho in 1973 and a very cold, wet spring in Montana in 1976, larch casebearer populations were greatly reduced in the two States. In many of the release locations in Montana, the very low numbers of casebearers may account for not recovering *A. pumila* in the samples. In Idaho, casebearer numbers are again increasing in 1977 and *A. pumila* parasitism reached highs of 40- to 50-percent in laboratory examinations. In many areas, the combination of *A. pumila* and other parasites may be sufficient to keep the casebearer from building up to its former epidemic levels for periods of long duration.

## Other Exotic Parasite Introductions from 1972 through 1976

In 1972, the Pacific Northwest and Intermountain Forest and Range Experiment Stations began a program of introducing other exotic parasites--initially *Chrysocharis laricinellae* (Ratz.) and *Dicladocerus westwoodii* Westwood (Hymenoptera: Eulophidae) (Ryan and Denton 1973). Collections of parasitized larch casebearer larvae and pupae were made at several locations in Austria and near Cinderford, Gloucestershire, England, through arrangements with H. Pschorn-Walcher of the European Station, Commonwealth Institute of Biological Control, Delemont, Switzerland. Material was shipped to the Research Institute, Canadian Department of Agriculture, Belleville, Ontario, where adult parasites emerged and were forwarded to Corvallis, Oreg., for propagation and distribution by Roger B. Ryan.

A total of 513 *D. westwoodii* and 240 *C. laricinellae* was released in Washington and Idaho (table 4). Parasite releases were made on predesignated study plots to facilitate subsequent evaluation of parasite effectiveness. Unfortunately, by June 7, when the first shipment of *D. westwoodii* arrived, the bulk of the casebearer population on most plots had pupated and passed the stage where they were susceptible to parasitism. However, larvae were still present in the Charley Creek plot, and *D. westwoodii* was released there. *C. laricinellae* was first available for release on June 17. Because synchronization with the susceptible casebearing larvae was poor, adults were held in the laboratory until this stage was again available in September. Meanwhile, separate colonies of *C. laricinellae* from Austria and England were established on the larch casebearer in the laboratory (fig. 27). The Austrian colony furnished the individuals for the September 26 release. A third colony of *C. laricinellae* was started from individuals collected from the casebaerer in Wisconsin by H. C. Coppel and J. W. Mertins. The numbers of parasites in the English and Wisconsin colonies were too low for release in 1972 and were maintained for subsequent release.

Table 4.--*Release of* Dicladocerus westwoodii *and* Chrysocharis laricinellae *against larch casebearer in Washington and Idaho, 1972*

| Liberation site | Source | Date of release | Number released<br>Male | <br>Female | <br>Total |
|---|---|---|---|---|---|
| *D. westwoodii:* | | | | | |
| Charley Creek, 15 miles south Pomeroy, Wash. 46°115'N, 117°30'W | Austria | June 7 | 116 | 57 | 173 |
| | England | June 7 | 44 | 26 | 70 |
| U.S. Highway 95, 25 miles north Moscow, Idaho | Austria | June 27 | 132 | 79 | 211 |
| | | July 6 | 31 | 28 | 59 |
| *C. laricinellae:* | | | | | |
| U.S. Highway 95, 25 miles north Moscow, Idaho 47°02'N, 116°52'W | Austria | Sept. 13 | 10 | 90 | 100 |
| | lab reared (Austrian stock) | Sept. 26 | 53 | 87 | 140 |

In 1973 and 1974, additional releases of *Chrysocharis laricinellae*, *Necremnus etalarus* (Walker), *Elachertus argissa* (Walker), *Dicladocerus* "A" (subsequently described s *D. japonicus* Yoshimoto), and *Diadegma laricinellae* (Strobel) were made in Washington, daho, and Montana. Details of obtaining these parasites were given by Ryan and others 1975). Locations and number of specimens released are shown in Appendix table 6.

A similar program was continued in 1975 and 1976 (Ryan and others 1977). Release ocations, species, and numbers of parasites are listed in Appendix table 7.

## Success of Other Exotic Parasite Releases

Ryan (personal communication) reported recovering *Dicladocerus* (probably *westwoodii*), . *laricinellae*, and *E. argissa* on some of his plots in Oregon. In 1977, single specimens of *D. japonicus* and *E. argissa* were recovered in two of the Idaho release locations. one of the other exotic parasites have been recovered in the Northern Region releases, ith the possible exception of *C. laricinellae*.

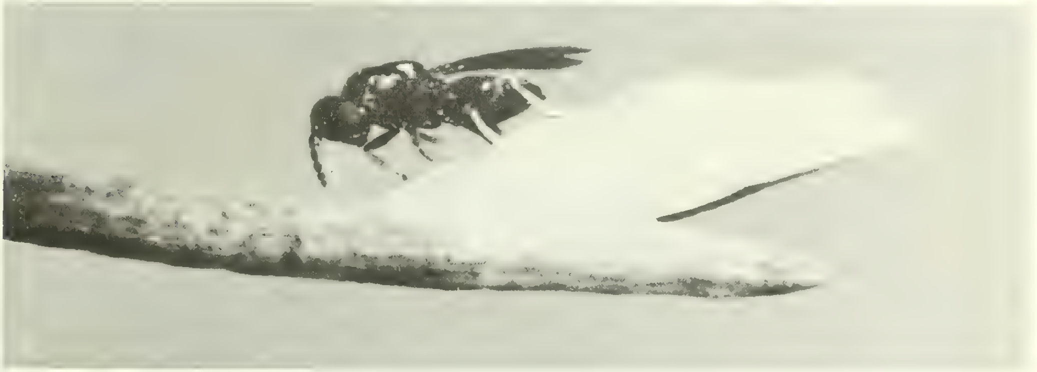


*Figure 27.--Female* Chrysocharis laricinellae *ovipositing on a larch casebearer larva inside its case.*

The situation regarding *C. laricinellae* has been very surprising. It was first ecovered near Hope, Idaho, in 1972 from casebearer samples sent to Corvallis, Oreg., rear *Agathis pumila* (Ryan and others 1974). This was prior to the 1972 releases *C. laricinellae* in Idaho. There is no explanation as to how this parasite became stablished in the West. Since then, *C. laricinellae* has been found in increasing numbers throughout the casebearer infestation in Montana and Idaho, and it has been ecovered in British Columbia. In 1977, it was found in 94 of the locations that were ampled to determine the establishment of *Agathis pumila*. This is an important parasite the casebearer in the East and, along with *A. pumila*, *C. laricinellae* apparently will an important biocontrol agent in western larch forests.

## Native Parasitism

Increasing numbers of native species of parasites are parasitizing the larch casebearer. As previously mentioned, in the area originally infested, only three species parasites were recovered in 1958. By 1968, aggregate native parasitism had increased 17 percent and the number of species recovered had increased to 16 (Denton 1972).

Bousfield and Lood (1973) recovered 19 species of native parasites from Montana, northern Idaho, and northeastern Washington. In British Columbia, Canada, Miller and Finlayson (1974) recorded 32 species of hymenopterous parasites; however, it is questionable if several of these species are actually parasites of the larch casebearer. For example, *Anaphes* sp. (Mymaridae) is a known egg parasite and probably emerged from eggs of aphids that may have been on the foliage.

Following is a list of 39 native parasites that have been reared in the West:

| | |
|---|---|
| Ichneumonidae | *Scambus decorus* Wiley |
| | *Scambus transgressus* (Holmgren) |
| | *Scambus* sp. |
| | *Gelis tenellus* (Say) |
| | *Gelis* sp. |
| | *Campoplex rufipes* (Provancher) |
| | *Pristomerus* sp. |
| | *Itoplectis evetriae* Viereck |
| | *Itoplectis vesca* Townsend |
| | *Bathythrix* sp. |
| | *Acrolyta* sp. (?) |
| | *Hyposoter* sp. (?) |
| Braconidae | *Bracon pygmaeus* Provancher |
| Chalcididae | *Spilochalcis albifrons* (Walsh) |
| Eulophidae | *Dicladocerus nearcticus* Yoshimoto |
| | *Dicladocerus occidentalis* Yoshimoto |
| | *Dicladocerus pacificus* Yoshimoto |
| | *Tetrastichus coerulescens* Ashmead |
| | *Tetrastichus dolosus* Gahan |
| | *Tetrastichus ecus* Walker |
| | *Hyssopus* sp. |
| | *Achrysocharella silvia* Girault |
| | *Achrysocharella* sp. |
| | *Zagrammosoma americanum* Girault |
| | *Eulophus* sp. |
| | *Euderus cushmani* (Crawford) |
| | *Elachertus proteoteratis* (Howard) |
| | *Cirrospilus pictus* (Nees) |
| | *Melittobia* sp. (?) |
| | *Diglyphus* sp. (?) |
| Pteromalidae | *Habrocytus phycidis* Ashmead |
| | *Mesopolobus* sp. |
| | *Catolaccus aeneoviridis* (Girault) |
| | *Cyrtogaster vulgaris* Walker |
| | Pteromalini tribe (genus? species?) |
| Diapriidae | *Telenomus* sp. |
| | *Trissolcus* sp. |
| Platygasteridae | *Platygaster* sp. |
| Mymaridae | *Anaphes* sp. (?) |

Little is known about the biology of these native parasites and the identity of their "normal" hosts. No native parasites have been recovered in rearing or dissecting overwintering casebearer larvae, indicating that they attack the casebearer only once, in the spring. In past years, *Spilochalcis albifrons* has been the predominant native parasite; however, its main drawback is the disproportionate ratio of males to females when the casebearer is the host. This ratio was determined in 1974 as 68 males:1 female, and in 1975 as 74 males:no females.

Hansen (1977) studied the biology and behavior of *S. albifrons* for his doctoral dissertation at Washington State University. This is a general parasite, mainly of small lepidopterous insects, and attacks casebearer pupae. He attributed the high ratio of males to females to the host pupae being too small to initiate the proper behavioral response to stimulate the spermatheca of the female parasite to release sperm during oviposition, which resulted in all male progeny. Hansen concluded that, by itself, *S. albifrons* could not be an effective biocontrol agent of the casebearer.

Undoubtedly, the number of species of native parasites attacking the casebearer in the West will continue to increase--additional species are being recovered periodically. However, the ultimate role of the native parasite complex as a controlling factor is questionable. In the East, Webb (1953) reported more than 50 species of native parasites reared from larch casebearer. However, Webb did note, "The native parasites... are chiefly notable for the large number of species represented rather than for achieving effective control."

## Native Predation

The amount and kinds of predation are difficult to determine. Unless a predator is actually observed attacking the casebearer, it cannot be said with certainty what its prey is. Thus, information on predation has been gained by direct observations. The major arthropod predators are mites and hemipterous bugs; to a far lesser degree, spiders capture casebearer larvae and ants have been observed dragging larvae to their nests when the larvae have been forced to migrate in search of food. In 1973, "the year of the yellow jacket," wasps by the thousands were observed searching larch trees in ate summer and carrying away larvae that had constructed their cases.

Egg predation, especially by a species of voracious large red mite (*Bdella muscorum* wing), is an important factor in natural control. This predator, along with hemipterons, lso attacks casebearer larvae, especially when circumstances cause the casebearer to ander without the protection of its case. This occurs mainly in the spring when maturng larvae occasionally leave their cases and search for larger needles to construct new ases that will accommodate their size (commonly, gussets are inserted in their existing ases).

In a recent study (Denton 1976), casebearer egg mortality averaged 22 percent mostly caused by predation), with a range of 15 to 28 percent (table 5). Other workers ave recorded varying amounts of egg mortality. In Europe, Eidmann (1965) found 3 to 8 percent; Baird (1923) found up to 25 percent in Connecticut, mostly due to apparent nfertility; Webb (1953) found 14 to 16 percent egg predation in New Brunswick, Canada.

Table 5.--Larch casebearer egg mortality, Coram Experimental Forest, Mont., 1975

| Plot spacing | Eggs examined | Eggs viable | Eggs dead (empty) | Mortality |
|---|---|---|---|---|
| *Feet* | - - - - - - - - | *Number* | - - - - - - - - | *Percent* |
| 15x15 | 200 | 157 | 43 | 22 |
| 15x15 | 200 | 171 | 29 | 15 |
| 11x11 | 200 | 166 | 34 | 17 |
| 11x11 | 200 | 160 | 40 | 20 |
| 7x7 | 200 | 149 | 51 | 26 |
| 7x7 | 200 | 157 | 43 | 22 |
| 5x5 | 200 | 145 | 55 | 28 |
| 5x5 | 200 | 155 | 45 | 23 |
| Unthinned | 200 | 159 | 41 | 21 |
| Unthinned | 200 | 147 | 53 | 27 |
| Totals | 2,000 | 1,566 | 434 | |
| Average | | | | 22 |

The most important arthropods observed preying on various stages of larch casebearer were:

- Hemiptera
  - Miridae
    - *Deraecoris* sp.
    - *Phytocoris* sp.
  - Anthocoridae
    - *Anthocoris* sp.
- Arachnida
  - Bdellidae
    - *Bdella muscorum* Ewing
  - Erythraeidae
    - *Balaustium* sp.

Birds are probably important vertebrate predators of larch casebearer; however, their importance as a regulatory factor has not been studied in the West. In Wisconsin, Sloan and Coppel (1968) reported that birds feeding on overwintering larvae were probably responsible for a 23.5 percent mortality of larch casebearer. Of 32 species of birds tested, 13 fed on larch casebearers.

Curtis H. Halvorson (personal communication) of the U.S. Fish and Wildlife Service, Missoula, Mont., has made spring bird counts in thinned western larch areas from 1971 to 1977. A partial list of birds on the Coram Experimental Forest, Mont., includes 41 species, of which 17 are common on thinned plots where casebearer population data are collected. The 17 included warblers, thrushes, flycatchers, chickadees, and sparrow types. Although not verified as winter residents on the Experimental Forest, the junco and chickadee are common winter residents in western Montana. The chipping sparrow and most warblers usually arrive in early May.

Birds actually observed, collected, and photographed by movie camera as feeding on asebearer larvae and pupae include the mountain chickadee, dark-eyed junco, chipping parrow, and orange-crowned warbler. Additionally, one junco was observed June 27, 974, probing larch needle clusters and hopping among small branches. Casebearer moths ere present and the bird's behavior suggested it was taking the moths.

The four bird species verified by Halvorson as predators on the larch casebearer t Coram undoubtedly represent only a few of those using the casebearer to some degree. alvorson thought the four important for two reasons. They are present by early May, f not winter residents. Thus, they need food at a time when insects other than the asebearer are scarce. Second, they are among the few birds that seem to use thinned arch stands to any degree. Observations by Halvorson indicate that birds are much ess frequently observed within the thinned areas than at the edge or within adjacent nthinned sites where abundant shrubby vegetation provides a diverse habitat. The bservations apply to thinned larch stands where competing shrubby vegetation has also een cut down. Lack of nests in young larch trees further supports the impression that hinning done to enhance larch growth rate has impoverished the area for bird feeding nd nesting. Juncos seem most tolerant of the thinned areas but even so are more comon where shrubs are present. That juncos commonly nest on the ground may partially ccount for this tolerance.

Appendix table 8, "Larch casebearer vulnerability to birds," was prepared by alvorson with the help of the author to approximate and help visualize the phenology f casebearer development as it relates to assumed avian predation. Yearly variation n casebearer development is probably the rule but suggestions were made to include ormal variation. For example, 1975 was a particularly cold, wet spring and moths were till not in evidence above 3,700 ft (1128.5 m) as late as July 5.

# CHEMICAL CONTROL

Prior to the 1950's, few chemicals were available or had been tested against the asebearer. During the first 100 years after its appearance in North America, the comon recommendation for control was 1 part of liquid lime sulphur in 9 parts of water, pplied early in April before larch buds burst and casebearer larvae broke hibernation Herrick 1912; Britton 1924; Schaffner 1952). The authors recognized that this treatent was applicable only to individual ornamental trees, or small groups of trees, from e ground--the cost of controlling the casebearer under forest conditions was conidered economically impracticable. The possibility of aerial application of insectiides was not mentioned.

In the 1950's, newer chemicals, including several systemic insecticides, were ried against the casebearer--notably in Europe. Vité (1955) found that application f 0.05 percent Metasystox and 0.05 percent Systox killed 100 percent of first instar eedlemining larvae when applied by banding tree trunks with strips of cellulose and oaking the bandages with the chemicals. Weber (1966) also reported good casebearer ontrol with 0.01 percent Metasystox, sprayed on tree trunks in late July. Burst and wald (1955) and Ewald and Burst (1959) investigated the effects of DNC (dinitro-ortho-resol), BHC (benzene hexachloride), DDT, and malathion on the casebearer in Germany. 0.909 percent DNC spray applied before bud burst gave 99.6 percent kill. A 0.2 perent BHC emulsion spray killed about 89 percent of the larvae in March. A spray conaining a 0.06 percent mixture of DDT and BHC applied in April gave 92 percent morality. A 0.3 percent malathion spray, applied when moths were flying, apparently gave ood control. The effectiveness of a premature defoliation of larch trees in autumn as investigated, also, by applying 0.01 percent DNC spray on October 12. The needles ell within 2 weeks and no larvae were left on the trees.

The first attempt to control the casebearer by aerially spraying forested areas was in 1962 in Idaho, conducted jointly by the Northern Region Division of State and Private Forestry (now Forest Insect and Disease Management) and the Intermountain Forest and Range Experiment Station. Lindane (a gamma isomer of benzene hexachloride), DDT, and malathion were selected for the initial tests against fourth instar feeding larvae in mid-May. In these, and subsequent tests a Bell 47G-3 helicopter was used to apply the insecticides. We intended to spray in late April, shortly after the casebearer broke hibernation, to prevent the current year's defoliation. However, owing to inclement weather, snow, and mud at this time of year, favorable conditions for the tests did not occur until May 11. By that date much of the foliage had been consumed.

Results of the tests (table 6) showed that malathion was the most effective insecticide. Lindane, mixed in water, gave some control, but DDT was quite ineffective even when applied at more than 2 pounds per acre (2.25 kg/ha).

Table 6.--*Mortality of larch casebearer larvae from lindane, malathion, and DDT sprays applied by helicopter at the rate of 1 gallon per acre (9.4 liters/ha), May 1962*

| Plot No. | Insecticide and formulation | Prespray mortality | Postspray mortality[1] | |
|---|---|---|---|---|
| | | | Total | Corrected |
| | | - - - - - - - - - *Percent* - - - - - - - - - | | |
| 1 | 1/2 lb lindane/gal water | 0.4 | 44.6 | 44.2 |
| 2 | 1/4 lb lindane/gal water | 0.2 | 24.3 | 24.1 |
| 3 | 1 lb malathion/gal fuel oil | 0.4 | 86.2 | 85.8 |
| 4 | 1/2 lb malathion/gal fuel oil | 1.5 | 90.1 | 89.6 |
| 5 | 2 lb DDT/gal fuel oil | 2.0 | 17.8 | 15.8 |
| 6[2] | 1 lb DDT/gal fuel oil | 1.0 | -- | -- |
| Check | | 0.4 | 1.1 | -- |

[1] Calculated 10 days after spraying.

[2] Because of the ineffectiveness of DDT at 2 pounds per acre, mortality on the plot treated with 1 pound per acre was not determined.

Aerial spray tests were continued in 1963 against fourth instar larvae in May, using malathion, dimethoate, and phosphamidon, and against third instar larvae in September, using undiluted technical grade malathion. As in 1962, the spring tests could not be conducted until May 9 because of inclement weather.

The initial results of casebearer mortality in the spring tests seemed inconsistent (table 7). For example, malathion at 1/4 pound per acre (0.27 kg/ha) gave considerably better control than the 1/2 pound (0.23 kg) rate. However, in these tests, we were limited to sampling casebearer mortality on 10 western larch trees randomly scattered throughout each 10-acre (4.0 ha) spray plot. One or two trees receiving little or no spray deposit can strongly affect the average mortality estimate. Examination of deposit cards showed that some trees were either missed or received very little spray. In practically every instance where considerable numbers of living casebearer larvae were found, the cards showed little or no spray deposit. If these trees are discounted, excellent control was achieved with all insecticides (table 8).

The question rose about the possibility of fall treatments after the casebearer had constructed its case (third instar). This would permit taking advantage of better weather conditions. In the Northwest, generally there are several or more weeks of dry "Indian Summer" in September and October. This would increase the length of time for control operations, compared with about a 2-week period in the spring, and accessibility into areas to be treated would be greatly enhanced.

Table 7.--*Mortality of larch casebearer larvae from malathion, dimethoate, and phosphamidon applied by helicopter at the rate of 1 gallon per acre, (9.4 liters/ha) May 1963 (actual results)*

| Plot No. | Insecticide and formulation | Mortality | Control[1] |
|---|---|---|---|
| | | *Percent* | *Percent* |
| 1 | 1/2 lb malathion/gal fuel oil | 76.8 | |
| 2 | 1/2 lb malathion/gal fuel oil | 80.2 | |
| | Average | 78.5 | 76.7 |
| 3 | 1/4 lb malathion/gal fuel oil | 94.1 | |
| 4 | 1/4 lb malathion/gal fuel oil | 94.5 | |
| | Average | 94.3 | 93.8 |
| 5 | 1/2 lb dimethoate/gal water | 85.4 | |
| 6 | 1/2 lb dimethoate/gal water | 99.9 | |
| | Average | 92.6 | 92.0 |
| 7 | 1/4 lb dimethoate/gal water | 85.6 | |
| 8 | 1/4 lb dimethoate/gal water | 83.7 | |
| | Average | 84.6 | 83.3 |
| 9 | 1 lb phosphamidon/gal fuel oil | 99.9 | 99.9 |

[1] Computed by Abbott's (1925) formula:

$$\text{Percent control} = \frac{\%\ \text{mortality in treatment} - \%\ \text{mortality in check*}}{100\% - \%\ \text{mortality in check*}}$$

*Natural mortality averaged 7.5 percent in two check plots.

Table 8.--*Mortality of larch casebearer larvae from malathion, dimethoate, and phosphamidon applied by helicopter at the rate of 1 gallon per acre (9.4 liters/ha) May 1963 (modified results)*

| Plot No. | Insecticide and formulation | Mortality | Control[1] |
|---|---|---|---|
| | | *Percent* | *Percent* |
| 1 | 1/2 lb malathion/gal fuel oil | 99.8 | |
| 2 | 1/2 lb malathion/gal fuel oil | 97.6 | |
| | Average | 98.7 | 98.6 |
| 3 | 1/4 lb malathion/gal fuel oil | 99.3 | |
| 4 | 1/4 lb malathion/gal fuel oil | 94.5 | |
| | Average | 96.9 | 96.6 |
| 5 | 1/2 lb dimethoate/gal water | 95.5 | |
| 6 | 1/2 lb dimethoate/gal water | 99.9 | |
| | Average | 97.7 | 97.5 |
| 7 | 1/4 lb dimethoate/gal water | 97.6 | |
| 8 | 1/4 lb dimethoate/gal water | 99.1 | |
| | Average | 98.3 | 98.2 |
| 9 | 1 lb phosphamidon/gal fuel oil | 99.9 | 99.9 |

[1] Computed by Abbott's (1925) formula (see table 7).

The author and Mr. Homer J. Hartman (retired; then Chief, Northern Region Division of Pest Control) consulted with Dr. Alexander T. Sinclair (retired; then Head of Field Research, Development and Technical Service, American Cyanamid Company) who proposed a low-volume test of technical grade (95 percent) malathion at a dosage rate of 1 pint (16 fl oz) per acre (1169 ml/ha).

The exploratory test was conducted on September 24, 1963, on 60 acres (24.3 ha) of a heavily infested western larch forest near Athol, Idaho. Actual dosage rate was determined to be 18 fluid ounces per acre (1,315 ml/ha). Casebearer larval mortality, checked 1 week later, showed that the test was an unqualified success. Branch samples collected at three crown levels from each of 10 trees showed no surviving larvae. Results were documented further by photographs taken in September 1963 and June 1964. In September, the larch trees were completely brown; the following June the forest was completely green, and no casebearers could be found.

In 1964, a formal test of technical grade malathion was conducted against spring-feeding fourth instar larvae on May 12 (Denton and Tunnock 1968). Low-volume applications of 8 fluid ounces per acre (585 ml/ha)(subsequently such low dosage rates were termed ultra-low volumes) were compared to "standard" applications of 1/2-pound malathion per gallon of fuel oil per acre (0.57 kg/9.35 liter/ha). Undiluted malathion gave 95.6 percent control, compared to 100 percent control of the 1/2-pound (0.23 kg) dosage rate (table 9). Since 1968, this method of controlling larch casebearer has been recommended by the U.S. Department of Agriculture in Agricultural Handbook No. 331, "Suggested Guide for Use of Insecticides to Control Insects Affecting...Forests..." On January 1, 1975, the Environmental Protection Agency also approved ultra-low volume application of malathion for spring casebearer control (EPA Registration No. 241-208-AA

In 1970, laboratory tests of six insecticides were conducted by the Pacific Southwest Forest and Range Experiment Station to find candidate insecticides as toxic or mor toxic than malathion to larch casebearer larvae (Lyon and May 1970). All six were high toxic at less than 1.05 μg/cm$^2$ (the equivalent of 1.5 ounces per acre). In decreasing order of toxicity the insecticides tested were: Zectran, malathion, Sumithion, pyrethrins, Matacil, and Gardona. A dosage of 2 ounces per acre (105.1 g/ha) was suggested for field trials of the three most toxic materials.

In cooperation with Dr. Sidney R. Siemer of Abbott Laboratories, Fresno, Calif., a preliminary evaluation was made of Dipel (a commercial preparation of *Bacillus thuringiensis*) for control of fourth instar casebearer larvae on May 23, 1972. Dipel wettable powder was applied with a backpack mist sprayer at dosage rates of 1 (0.45 kg) 1/2 (0.23 kg), 1/4 (0.11 kg), and 1/10 (0.05 kg) pounds per 100 gallons (378.5 liters) of water. Casebearer control (based upon the number of moths that emerged) decreased from about 50 percent at the 1-pound (0.45 kg) dosage to 0 percent at the 1/10-pound (0.05 kg) rate, compared to an untreated check treatment and a second treatment where water only was sprayed on the foliage.

The conclusion was that under the conditions of this test, Dipel did not give satisfactory control of the casebearer. However, it is possible that owing to the lateness of the test, many larvae had nearly completed their development and were ready to pupate; thus, they did not ingest sufficient amounts of Dipel to cause mortality. It was observed that within minutes after applying the 1- and 1/2-pound (0.45 and 0.23 kg) rates, casebearer larvae appeared irritated and either left their feeding sites or extended their cases to the fullest length as though airing or drying their bodies (thi reaction was not observed on the treatment where water only was applied). The above dosage rates also apparently delayed further casebearer development and subsequent emergence of moths, compared to the check treatments. *Bacillus thuringiensis* deserves further testing against the casebearer.

Table 9.--*Control of larch casebearer by aerial sprays of malathion, Trout Creek, Mont., May 1964*

| Plot No. | Spray dosage rate/acre | Mortality | Control[1] |
|---|---|---|---|
| | | Percent | |
| 1 | 8 fl oz (0.6 lb actual) | 99.6 | |
| 2 | 8 fl oz (0.6 lb actual) | 91.9 | |
| | Average | 95.8 | 95.6 |
| 3 | 0.5 lb actual/gal fuel oil (twice)[2] | 100.0 | |
| 4 | 0.5 lb actual/gal fuel oil | 100.0 | |
| | Average | 100.0 | 100.0 |
| 5 | Check | 2.2 | |
| 6 | Check | 7.9 | |
| | Average | 5.0 | |

[1] As calculated by Abbott's formula (see table 7).

[2] Total dosage about 1 lb/2 gal fuel oil per acre.

A preliminary ground test of acephate (trade name Orthene), a relatively new systemic insecticide, was conducted against second-instar needlemining casebearer larvae on August 23, 1974 (Livingston and Ludeman 1974). When individual trees were sprayed until they were dripping wet, heavy (0.75 pounds per 100 gallons of water; 0.34 kg/378.5 liters) and medium (0.375 pounds per 100 gallons of water; 0.17 kg/378.5 liters) dosages gave 100 percent casebearer mortality.

Laboratory bioassay tests of Orthene were made on second-instar needlemining casebearer larvae in the spring of 1975 by the Insecticide Evaluation Project of the Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif. Procedures for forced rearing of casebearer adults and subsequent oviposition on potted western larch seedlings were developed in a greenhouse at the Moscow Forestry Sciences Laboratory. A dosage rate of 0.24 to 0.27 ounces per acre (16.8 to 18.9 g/ha) caused 50 percent mortality of needlemining larvae, and 0.88 to 1.01 ounces per acre (61.7 to 70.8 g/ha) reduced the laboratory population by 90 percent (Page and others, In press).

On September 11, 1975, the first aerial spray test of Orthene was conducted against needlemining casebearer larvae at Farragut State Park, Idaho (Washburn and others 1977). Formulation and dosage rate were 1 pound (0.45 kg) of Orthene in 1 gallon (3.78 liters) of water, applied by helicopter at the rate of 1 gallon per acre (9.4 liters/ha). This treatment was replicated three times on 20-acre (8.1 ha) plots, and results were compared with natural casebearer mortality on three check plots.

Despite excessive wind velocities on the morning of the test, causing considerable spray drift, Orthene appeared very effective in reducing casebearer populations from 92.14 to 99.93 percent (table 10). Check plots 2 and 6 (that were downwind of the sprayed plots) received 0.01 gallons of spray per acre (0.09 liters/ha), as recorded on spray deposit cards. This dosage was still sufficient to cause considerable casebearer mortality (table 10), and suggests that lower concentrations of Orthene than were used in this test would be effective against the casebearer needlemining stage.

Table 10.--*Larch casebearer pre-and postspray population densities, survival rates, and mortality estimates from application of Orthene, September 1975*

| Treatment and plot | LCB density | | | | Survival ratio | Corrected percent mortality[3] |
|---|---|---|---|---|---|---|
| | Prespray[1] | | Postspray[2] | | | |
| | Mean | Standard deviation | Mean | Standard deviation | | |
| | | | Sprayed | | | |
| 1 | 47.19 | 41.86 | 0.18 | 1.24 | 0.0038 | 99.56 |
| 3 | 238.68 | 161.80 | .15 | 0.53 | .0006 | 99.93 |
| 5 | 110.52 | 91.11 | 7.52 | 18.90 | .0680 | 92.14 |
| | | | Checks | | | |
| 2 | 226.17 | 136.31 | 119.20 | 66.07 | .5270 | 39.08 |
| 4 | 202.87 | 131.64 | 175.50 | 95.48 | .8651 | 13.49 |
| 6 | 71.30 | 48.58 | 11.00 | 17.37 | .1543 | 82.22 |

[1] Needlemining larvae per 100 fascicles.

[2] Overwintering casebearing larvae per 100 fascicles.

[3] Corrected for natural mortality in check plot 4.

In 1976, a similar test of Orthene was conducted against the casebearer needlemining stage near La Grande, Oreg., by the Pacific Southwest Forest and Range Experiment Station. Formulation and dosage rate were 1/2 pound of Orthene in 1 gallon of water (0.23 kg/3.78 liters), applied by helicopter at the rate of 1 gallon per acre (9.4 liters/ha). Three plots, 50 acres (20.2 ha) in size, were sprayed and one plot was left untreated in each of three blocks of western larch stands. Spraying was done on September 9, 12, and 13. While apparently not as successful as the 1975 test, the 1/2-pound (0.23 kg) dosage caused an average of 91.4 to 93.1 percent reduction in casebearer needlemining populations (table 11). Future tests of Orthene are planned against spring-feeding fourth instar casebearer larvae.

Table 11.--*Larch casebearer pre- and postspray population densities and mortality estimation from applications of Orthene, September 1976*

| Date | Treatment[1] sequence and lb/actual acre | No. larvae/100 fascicles | | | | Reduction |
|---|---|---|---|---|---|---|
| | | Prespray | | Postspray | | |
| | | x | Range | x | Range | x |
| | | | | | | *Percent* |
| 9/9 | 1st Orthene 75 S 0.5 | 156.3 | 145.6-166.9 | 10.6 | 5.3-15.6 | 93.1 |
| 9/12 | 2nd Orthene 75 S 0.5 | 172.6 | 117.1-256.2 | 18.6 | 2.3-46.0 | 91.4 |
| 9/13 | 3rd Orthene 75 S 0.5 | 169.4 | 120.2-245.5 | 15.4 | 1.3-26.7 | 91.7 |
| | Untreated | 217.4 | 163.2-315.6 | 123.9 | 86.4-152.5 | 40.7 |

[1] A mixture of 90% water and 10% ethylene glycol served as carrier.

# FUTURE PROSPECTS FOR LARCH CASEBEARER INFESTATIONS IN THE WEST

If this publication had been written 10 years ago in 1967, the prognosis for larch casebearer infestations would have been quite different than in 1977. Initially, there were few biocontrol agents operating against the casebearer in the early years following its introduction into Idaho. In addition, the first 10 years from 1957 to 1967 were climatically ideal for a tremendous buildup and spread of the casebearer throughout western larch forests in the Northern Region and adjacent areas. Although the parasite *Agathis pumila* was introduced and distributed throughout the infestation, and an increasing number of native parasites began to attack the casebearer, their overall effectiveness was not apparent because of the huge casebearer population already built up.

In 1967, growth loss and larch mortality were becoming very serious in northern Idaho. Besides direct mortality, indirect mortality through loss of dominance was imminent. The future for western larch management seemed uncertain. Some National Forest Supervisors stated that they were discontinuing the culture and planting of larch stands until the casebearer problem was solved. Because larch stands are scattered, direct control with chemicals, although possible, would be very costly and moreover provide only temporary relief.

In 1967, a severe drought drastically reduced casebearer populations. Although casebearer numbers built up again so that defoliation was heavy from 1970 to 1973, a record drought in 1973 decimated the infestation again, especially in northern Idaho. Since then, four species of parasites have become increasingly important biocontrol agents. The imported *A. pumila* has been recovered in increasing numbers far distant from the original release locations. Another exotic parasite, *Chrysocharis laricinellae*, is also rapidly increasing in numbers and spreading throughout the casebearer infestation. Two native parasites, *Spilochalcis albifrons* and *Dicladocerus nearcticus*, are numerous in many localities and show promise of exerting considerable control.

Thus, in 1977, the outlook for future larch casebearer infestations is quite different than 10 years ago. Generally, the casebearer is again increasing in numbers; however, even if climatic conditions are favorable for a number of years, natural factors, including weather and parasitism, may prevent the populations from reaching the high levels of the past. Undoubtedly, outbreaks will occur, but if they follow a pattern similar to that reported by Webb (1953) in the East, they will be of shorter duration and the interval between them will be longer. As in the case of native insect pests, forest managers will have to evaluate each epidemic and decide how to deal with it.

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# APPENDIX

Table A1.--*Examination of western larch trees heavily infested with larch casebearer larvae within the headwaters of Marble Creek, Idaho, to determine cause of deterioration, 1967*

| Site | Tree number | d.b.h. | Tree height | Crown class | Damage class | Insects other than casebearer | Culture results[1] |
|---|---|---|---|---|---|---|---|
| | | *Inches* | *Feet* | | | | |
| 1 | 1 | 5.3 | 35 | Intermediate | Dead | Few T.v.[2] | A.m. |
| | 2 | 7.1 | 40 | Intermediate | Severe | -- | N |
| | 3 | 6.9 | 35 | Codominant | Severe | -- | Y |
| | 4 | 7.3 | 40 | Codominant | Severe | -- | Y |
| | 5 | 5.0 | 32 | Codominant | Severe | -- | Y |
| | 6 | 7.2 | 40 | Codominant | Medium | -- | N |
| | 7 | 3.7 | 22 | Intermediate | Dead | Few secondaries | A.m. |
| | 8 | 6.9 | 33 | Intermediate | Severe | -- | B |
| | 9 | 3.5 | 20 | Intermediate | Dead | Few secondaries | A.m. |
| | 10 | 5.1 | 22 | Intermediate | Medium | -- | A.m. |
| | 11 | 8.1 | 45 | Codominant | Sparse | -- | B |
| | 12 | 10.6 | 45 | Dominant | None | -- | Y |
| 2 | 1 | 7.2 | 32 | Open grown | Sparse | -- | N |
| | 2 | 6.5 | 35 | Codominant | Medium | -- | N |
| | 3 | 3.5 | 22 | Codominant | Dead | Few T.v. | A.m. |
| | 4 | 7.4 | 35 | Open grown | Medium | -- | Y |
| | 5 | 4.8 | 25 | Open grown | Severe | -- | A.m. |
| | 6 | 5.5 | 25 | Open grown | Dead | Many T.v. | A.m. |
| | 7 | 8.8 | 32 | Open grown | Sparse | -- | N |
| | 8 | 6.0 | 30 | Intermediate | Dead | Few T.v. | Y |
| | 9 | 6.9 | 35 | Codominant | Sparse | -- | B |
| | 10 | 4.4 | 30 | Codominant | Dead | T.v. had emerged | A.m. |
| | 11 | 6.5 | 40 | Open grown | Sparse | -- | N |
| | 12 | 8.5 | 42 | Dominant | None | -- | N |
| 3 | 1 | 6.0 | 22 | Open grown | Dead | T.v. in collar | Y |
| | 2 | 8.0 | 35 | Open grown | Dead | T.v. in collar | Y |
| | 3 | 9.0 | 35 | Open grown | Medium | -- | B |
| | 4 | 11.1 | 40 | Open grown | Severe | -- | Y |
| | 5 | 8.4 | 32 | Open grown | Medium | -- | Y |
| | 6 | 5.5 | 20 | Open grown | Severe | -- | A.m. |
| | 7 | 6.9 | 28 | Open grown | Severe | -- | N |
| | 8 | 8.6 | 35 | Open grown | Dead | Many T.v. | N |
| | 9 | 5.6 | 25 | Open grown | Severe | -- | N |
| | 10 | 7.2 | 35 | Dominant | Severe | -- | N |
| | 11 | 10.0 | 40 | Open grown | None | -- | Y |
| | 12 | 6.4 | 27 | Open grown | None | -- | N |

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[1] A.m. = *Armillaria mellea*; B = bacteria; Y = yeast; N = no growth.

[2] T.v. = the western larch borer, *Tetropium velutinum* Lec.

Table A2.--*Examination of western larch trees heavily infested with larch casebearer near Falls, Idaho, to determine cause of deterioriation, 1967*

| Site | Tree number | d.b.h. | Tree height | Crown class | Damage class | Insects other than casebearer | Culture results[1] |
|---|---|---|---|---|---|---|---|
| | | *Inches* | *Feet* | | | | |
| 1 | 1 | 4.0 | 17 | Dominant | Medium | -- | N |
| | 2 | 3.0 | 15 | Dominant | Sparse | -- | N |
| | 3 | 5.0 | 35 | Dominant | Medium | -- | A.m. |
| | 4 | 8.0 | 36 | Dominant | Sparse | -- | N |
| | 5 | 6.0 | 35 | Dominant | Sparse | -- | N |
| | 6 | 6.0 | 24 | Dominant | Sparse | -- | B |
| | 7 | 3.0 | 20 | Intermediate | Medium | -- | B |
| | 8 | 7.0 | 30 | Codominant | Sparse | -- | A.m. |
| | 9 | 6.0 | 35 | Suppressed | Sparse | -- | N |
| | 10 | 7.0 | 38 | Intermediate | Medium | -- | Y |
| | 11 | 6.0 | 30 | Dominant | None | -- | Y |
| | 12 | 9.0 | 35 | Dominant | None | -- | N |
| 2 | 1 | 5.0 | 18 | Codominant | Medium | -- | A.m. |
| | 2 | 8.0 | 30 | Dominant | Sparse | -- | N |
| | 3 | 4.5 | 25 | Dominant | Medium | -- | N |
| | 4 | 3.5 | 22 | Dominant | Sparse | -- | N |
| | 5 | 3.0 | 22 | Dominant | Medium | -- | N |
| | 6 | 5.0 | 28 | Dominant | Sparse | -- | N |
| | 7 | 6.0 | 28 | Intermediate | Sparse | -- | Y |
| | 8 | 9.0 | 42 | Domiannt | Sparse | -- | B |
| | 9 | 3.5 | 22 | Intermediate | Sparse | -- | N |
| | 10 | 4.0 | 20 | Dominant | Severe | -- | A.m. |
| | 11 | 3.0 | 20 | Intermediate | None | -- | N |
| | 12 | 4.5 | 30 | Dominant | None | -- | N |
| 3 | 1 | 3.5 | 21 | Intermediate | Severe | -- | A.m. |
| | 2 | 4.0 | 22 | Intermediate | Medium | -- | B |
| | 3 | 4.5 | 30 | Dominant | Sparse | -- | B |
| | 4 | 4.0 | 35 | Intermediate | Severe | -- | N |
| | 5 | 3.0 | 16 | Dominant | Severe | -- | N |
| | 6 | 3.5 | 26 | Dominant | Medium | Many T.v.[2] | N |
| | 7 | 4.0 | 25 | Codominant | Severe | -- | N |
| | 8 | 3.0 | 20 | Codominant | Severe | -- | N |
| | 9 | 7.0 | 40 | Dominant | Sparse | -- | N |
| | 10 | 4.0 | 22 | Dominant | Sparse | -- | Y |
| | 11 | 3.0 | 22 | Intermediate | None | -- | N |
| | 12 | 7.0 | 38 | Dominant | None | -- | N |

[1] A.m. = *Armillaria mellea*; B = bacteria; Y = yeast; N = no growth.

[2] T.v. = the western larch borer, *Tetropium velutinum* Lec.

Table A3.--*Collections of* Agathis pumila *parasites in rearing cages at Sandpoint, Idaho, 1964*

| Month | Day | Males | Females | Percent females | Total | Cumulative total |
|---|---|---|---|---|---|---|
| June | 30 | 1 | 0 | 0 | 1 | 1 |
| July | 1 | 12 | 0 | 0 | 12 | 13 |
| | 2 | 18 | 0 | 0 | 18 | 31 |
| | 3 | 9 | 0 | 0 | 9 | 40 |
| | 4 | 150 | 0 | 0 | 150 | 190 |
| | 5 | 26 | 0 | 0 | 26 | 216 |
| | 6 | 311 | 55 | 15 | 366 | 582 |
| | 7 | 400 | 70 | 15 | 470 | 1,052 |
| | 8 | 63 | 12 | 16 | 75 | 1,127 |
| | 9 | 185 | 40 | 18 | 225 | 1,352 |
| | 10 | 684 | 456 | 40 | 1,140 | 2,492 |
| | 11 | 475 | 316 | 40 | 791 | 3,283 |
| | 12 | 640 | 640 | 50 | 1,280 | 4,563 |
| | 13 | 360 | 800 | 69 | 1,160 | 5,723 |
| | 14 | 266 | 564 | 68 | 830 | 6,553 |
| | 15 | 127 | 508 | 80 | 635 | 7,188 |
| | 16 | 46 | 90 | 66 | 136 | 7,324 |
| | 17 | 151 | 429 | 74 | 580 | 7,904 |
| | 18 | 128 | 407 | 76 | 535 | 8,439 |
| | 19 | 95 | 202 | 68 | 297 | 8,736 |
| | 20 | 60 | 314 | 84 | 374 | 9,110 |
| | 21 | 61 | 242 | 80 | [illegible] | 9,413 |
| | 22 | 25 | 100 | 80 | 125 | 9,538 |
| | 23 | 22 | 136 | 86 | 158 | 9,696 |
| | 24 | 39 | 176 | 82 | 215 | 9,911 |
| | 25 | -- | -- | -- | -- | -- |
| | 26 | -- | -- | -- | -- | -- |
| | 27 | 18 | 92 | 84 | 110 | 10,021 |
| | 28 | 2 | 10 | | 12 | 10,033 |
| | | 4,374 | 5,659 | | 10,033 | |

Table A4.--*Liberations of* Agathis pumila *to propagate colonies of parasites for biological control of larch casebearer*

| Date, 1964 | Type of liberation: Trees | Type of liberation: Limbs | Type of liberation: Free | Casebearer egg population: Spur | Casebearer egg population: Total | *Agathis pumila* liberated: Male | *Agathis pumila* liberated: Female | Casebearer larvae hatched per spur | Percent parasitism effected |
|---|---|---|---|---|---|---|---|---|---|
| | *Cage No.* | | *Plot* | - - - - | - - - - | *Number* | - - - - | - - - - | *Percent* |
| 7/10 | 2 | | | 2.6 | 18,720 | 236 | 90 | 0.42 | 12 |
| 7/11 | 5 | | | 1.5 | 13,650 | 182 | 132 | .08 | 24 |
| | 8 | | | 1.2 | 6,650 | 300 | 300 | .11 | 4 |
| | 10 | | | 1.9 | 15,770 | 100 | 100 | .12 | 0 |
| 7/12 | 1 | | | 1.1 | 5,380 | 50 | 50 | .50 | 16 |
| | 3 | | | 2.6 | 7,280 | 50 | 50 | .26 | 32 |
| | 6 | | | 1.3 | 8,540 | 50 | 50 | .35 | 4 |
| | 9 | | | 1.0 | 8,580 | 50 | 50 | .09 | 4 |
| | 11 | | | 3.2 | 20,160 | 100 | 100 | .37 | 4 |
| 7/13 | | [1]48 | | 4.2 | 9,240 | 24 | 104 | .22 | 0 |
| | | 50 | | 7.8 | 15,600 | 120 | 140 | .25 | 0 |
| 7/14 | | 46 | | 5.5 | 10,780 | 100 | 100 | .36 | 12 |
| | | 47 | | 3.6 | 12,600 | 60 | 140 | .30 | 16 |
| | | 49 | | 3.0 | 12,000 | 54 | 96 | .18 | 4 |
| | | 37 | | 3.3 | 16,300 | 60 | 140 | .36 | 36 |
| | | 39 | | 3.8 | 20,000 | 90 | 210 | .34 | 28 |
| | | 40 | | 2.5 | 12,400 | 60 | 120 | .28 | 20 |
| | | 41 | | 3.7 | 25,000 | 85 | 165 | .38 | 40 |
| | | 42 | | 3.1 | 21,600 | 85 | 165 | .30 | 32 |
| | | 43 | | 2.6 | 6,700 | 100 | 100 | .26 | 28 |
| | | 44 | | 3.3 | 19,300 | 100 | 200 | .22 | 36 |
| | | 45 | | 3.3 | 19,500 | 135 | 165 | .26 | 36 |
| 7/16,23 | | 36 | | 3.8 | 27,400 | 72 | 190 | .31 | 24 |
| 7/15,19 | | | Athol | -- | -- | 536 | 1,516 | -- | -- |
| 7/20 | | | McKay | 5.0 | -- | 92 | 195 | -- | -- |
| 7/21, 22,24 | | | Rock Creek | 5.0 | -- | 157 | 720 | -- | -- |
| Totals | | | | | | 3,048 | 5,388 | | |

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[1] Cages numbered 48, 50, 46, 47, and 49 were made of Saran screen; all other cages were made of cheesecloth.

Table A5.--*Collections of* Agathis pumila *parasites in a rearing cage at Sandpoint, Idaho, 1965*

| Date | Males | Cumulative total (males) | Females | Cumulative total (females) | Percent females | Daily total | Cumulative total (males and females) |
|---|---|---|---|---|---|---|---|
| 7/2 | 10 | 10 | | | | 10 | 10 |
| 7/3 | 103 | 113 | | | | 103 | 113 |
| 7/4 | 150 | 263 | | | | 150 | 263 |
| 7/5 | 350 | 613 | | | | 350 | 613 |
| 7/6 | 660 | 1,273 | | | | 660 | 1,273 |
| 7/7 | 1,000 | 2,273 | 3 | 3 | | 1,003 | 2,276 |
| 7/8 | 725 | 2,998 | 9 | 12 | 1 | 734 | 3,010 |
| 7/9 | 890 | 3,888 | 29 | 41 | 3 | 919 | 3,929 |
| 7/10 | 577 | 4,465 | 19 | 60 | 4 | 596 | 4,525 |
| 7/11 | 490 | 4,955 | 60 | 120 | 11 | 550 | 5,075 |
| 7/12 | 908 | 5,863 | 104 | 224 | 10 | 1,012 | 6,087 |
| 7/13 | 953 | 6,816 | 195 | 419 | 17 | 1,148 | 7,235 |
| 7/14 | 1,192 | 8,008 | 335 | 754 | 22 | 1,527 | 8,762 |
| 7/15 | 1,448 | 9,456 | 551 | 1,305 | 27 | 1,999 | 10,761 |
| 7/16 | 907 | 10,363 | 564 | 1,869 | 38 | 1,471 | 12,232 |
| 7/17 | 1,012 | 11,375 | 773 | 2,642 | 43 | 1,785 | 14,017 |
| 7/18 | 35 | 11,410 | 28 | 2,670 | 44 | 63 | 14,080 |
| 7/19 | 527 | 11,937 | 593 | 3,263 | 53 | 1,120 | 15,200 |
| 7/20 | 192 | 12,129 | 289 | 3,552 | 60 | 481 | 15,681 |
| 7/21 | 302 | 12,431 | 430 | 3,982 | 59 | 732 | 16,413 |
| 7/22 | 175 | 12,606 | 242 | 4,224 | 58 | 417 | 16,830 |
| 7/23 | 618 | 13,224 | 976 | 5,200 | 61 | 1,594 | 18,424 |
| 7/24 | 390 | 13,614 | 800 | 6,000 | 67 | 1,190 | 19,614 |
| 7/25 | 374 | 13,988 | 866 | 6,866 | 70 | 1,240 | 20,854 |
| 7/26 | 478 | 14,466 | 740 | 7,606 | 61 | 1,218 | 22,072 |
| 7/27 | 269 | 14,735 | 565 | 8,171 | 68 | 834 | 22,906 |
| 7/28 | 206 | 14,941 | 592 | 8,763 | 74 | 798 | 23,704 |
| 7/29 | 254 | 15,195 | 591 | 9,354 | 70 | 845 | 24,549 |
| 7/30 | 206 | 15,558 | 524 | 10,358 | 72 | 730 | 25,916 |
| 8/1 | 187 | 15,745 | 477 | 10,835 | 72 | 664 | 26,580 |
| 8/2 | 130 | 15,875 | 387 | 11,222 | 75 | 517 | 27,097 |
| 8/3 | 27 | 15,902 | 237 | 11,459 | 90 | 264 | 27,361 |
| 8/4 | 37 | 15,939 | 245 | 11,704 | 87 | 282 | 27,643 |
| 8/5 | 19 | 15,958 | 118 | 11,822 | 86 | 137 | 27,780 |
| 8/6 | 48 | 16,006 | 276 | 12,098 | 85 | 324 | 28,104 |
| 8/7 | 33 | 16,039 | 185 | 12,283 | 85 | 218 | 28,322 |
| 8/8 | 10 | 16,049 | 82 | 12,365 | 89 | 92 | 28,414 |
| 8/9 | - - - - - | - - - - - | - - - - - | No collection | - - - - - | - - - - - | - - - - - |
| 8/10 | 7 | 16,056 | 60 | 12,425 | 89 | 67 | 28,481 |
| 8/11 | 17 | 16,073 | 70 | 12,495 | 80 | 87 | 28,568 |
| 8/12 | 8 | 16,081 | 78 | 12,573 | 90 | 86 | 28,654 |
| 8/13 | 15 | 16,096 | 86 | 12,659 | 85 | 101 | 28,755 |
| 8/14 | 11 | 16,107 | 85 | 12,744 | 88 | 96 | 28,851 |
| 8/15 | 13 | 16,120 | 72 | 12,816 | 85 | 85 | 28,936 |
| 8/16 | 9 | 16,129 | 58 | 12,874 | 86 | 67 | 29,003 |
| 8/17 | 10 | 16,139 | 60 | 12,934 | 86 | 70 | 29,073 |
| 8/18 | 6 | 16,145 | 52 | 12,986 | 90 | 58 | 29,131 |
| 8/19 | 4 | 16,149 | 42 | 13,028 | 91 | 46 | 29,177 |
| 8/20 | 3 | 16,152 | 38 | 13,066 | 93 | 41 | 29,218 |
| 8/21 | 6 | 16,158 | 49 | 13,115 | 89 | 55 | 29,273 |
| 8/22 | 4 | 16,162 | 20 | 13,135 | 83 | 24 | 29,297 |
| 8/23 | - - - - - | - - - - - | - - - - - | No collection | - - - - - | - - - - - | - - - - - |
| 8/24 | 0 | 16,162 | 9 | 13,144 | 100 | 9 | 29,306 |
| 8/25 | - - - - - | - - - - - | - - - - - | No collection | - - - - - | - - - - - | - - - - - |
| 8/26 | 1 | 16,163 | 14 | 13,158 | 93 | 15 | 29,321 |
| 8/27 | 2 | 16,165 | 10 | 13,168 | 83 | 12 | 29,333 |
| 8/28 | - - - - - | - - - - - | - - - - - | No collection | - - - - - | - - - - - | - - - - - |
| 8/29 | - - - - - | - - - - - | - - - - - | No collection | - - - - - | - - - - - | - - - - - |
| 8/30 | - - - - - | - - - - - | - - - - - | No collection | - - - - - | - - - - - | - - - - - |
| 8/31 | | | 7 | 13,175 | | 7 | 29,340 |
| Totals | | 16,165 | | 13,175 | | | 29,340 |

Table A6.--*Releases of* Chrysocharis laricinellae, Necremnus metalarus, Elachertus argissa, Dicladocerus japonicus, *and* Diadegma laricinella *in Washington, Idaho, and Montana, 1973-74*

| Locality | Date released | Number released<br>Male | <br>Female | <br>Tota |
|---|---|---|---|---|
| *Chrysocharis laricinellae* (Ratz.) (Hymenoptera: Eulophidae) | | | | |
| Idaho:[1] | | | | |
| U.S. Hwy. 95, 25 mi N. Moscow<br>47°02' N. 116°52'W | Apr. 25, 1973 | 192 | 433 | 62 |
| | May 2, 1975 | 75 | 136 | 21 |
| | May 5, 1973 | 62 | 111 | 17 |
| | May 16, 1973 | 127 | 203 | 33 |
| | May 30, 1973 | 160 | 220 | 38 |
| | Sept. 11, 1973 | 33 | 172 | 20 |
| | Oct. 5, 1973 | 140 | 67 | 20 |
| 4.6 mi N. Troy<br>46°47'N. 116°48'W. | May 4, 1974 | 263 | 244 | 50 |
| 5.6 mi N. Troy<br>6°48'N. 116°47'W. | May 16, 1974 | 151 | 154 | 30 |
| Lochsa River, Eagle Mountain Pack Bridge<br>62.2 mi E. Kooskia<br>46°20'N. 115°8'W | May 30, 1974 | 147 | 154 | 30 |
| 3.4 mi E. Bovill<br>46°51'N. 116°20'W. | Sept. 27, 1974 | 33 | 276 | 30 |
| Montana:[2] | | | | |
| 4 mi N. Evaro<br>47°05'N. 114°04'W. | May 2, 1973 | 283 | 403 | 68 |
| | May 11, 1973 | 81 | 116 | 19 |
| | May 18, 1973 | 122 | 134 | 25 |
| | May 23, 1973 | 93 | 102 | 19 |
| | May 16, 1974 | 196 | 219 | 41 |
| | May 31, 1974 | 80 | 92 | 17 |
| | June 7, 1974 | 63 | 123 | 18 |
| Washington: | | | | |
| Colville Indian Reservation, E. Round Lake[3]<br>48°17'N. 118°18'W. | April 27, 1973 | 238 | 472 | 71 |
| | May 9, 1973 | 185 | 159 | 34 |
| | May 17, 1973 | 85 | 89 | 17 |
| | May 24, 1973 | 179 | 72 | 25 |
| | May 7, 1974 | 187 | 230 | 41 |
| | May 24, 1974 | 131 | 115 | 24 |
| | May 31, 1974 | 89 | 78 | 16 |
| | Sept. 26, 1974 | 1 | 112 | 11 |
| Charley Creek, 15 mi S. Pomeroy[4]<br>46°15'N. 117°30'W. | May 11, 1973 | 195 | 58 | 25 |
| | Sept. 25, 1973 | 119 | 81 | 20 |
| | Oct. 10, 1973 | 292 | 182 | 47 |
| | May 10, 1974 | 659 | 573 | 1,23 |
| | May 23, 1974 | 108 | 131 | 23 |
| | May 30, 1974 | 155 | 185 | 34 |
| | June 7, 1974 | 123 | 157 | 28 |
| | Sept. 20, 1974 | 122 | 192 | 31 |
| | Sept. 25, 1974 | 143 | 124 | 26 |

(continued next page; footnotes at end of tab

Table A6. (continued)

| Locality | Date released | Number released |  |  |
|---|---|---|---|---|
|  |  | Male | Female | Total |
| *Necremnus metalarus* (Walk.) (Hymenoptera: Eulophidae)[1] |  |  |  |  |
| Idaho: |  |  |  |  |
| 4.6 mi N. Troy<br>46°47'N. 116°48'W. | May 4, 1974 | 3 | 409 | 412 |
| 5.6 mi N. Troy<br>46°48'N. 116°47'W. | May 16, 1974 | 0 | 145 | 145 |
| 6 mi N. Troy<br>46°48'N. 116°47'W. | May 22, 1974 | 1 | 139 | 140 |
| Lochsa River, Eagle Mountain Pack Bridge<br>62.2 mi E. Kooskia<br>46°26'N. 115°8'W. | May 30, 1974 | 0 | 135 | 135 |
| 3.4 mi N. Bovill | Sept. 27, 1974 | 6 | 825 | 831 |
| 46°51'N. 116°20'W. | Oct. 9, 1974 | 5 | 386 | 391 |
| Montana: |  |  |  |  |
| 4 mi N. Evaro | May 16, 1974 | 1 | 406 | 407 |
| 47°05'N. 114°04'W. | May 31, 1974 | 0 | 175 | 175 |
|  | June 7, 1974 | 1 | 162 | 163 |
|  | Sept. 24, 1974 | 1 | 275 | 275 |
|  | Oct. 3, 1974 | 0 | 211 | 211 |
| Washington: |  |  |  |  |
| Colville Indian Reservation, E. Round Lake | May 7, 1974 | 1 | 378 | 379 |
| 48°17'N. 118°18'W. | May 24, 1974 | 0 | 124 | 124 |
|  | May 31, 1974 | 0 | 124 | 124 |
|  | Sept. 26, 1974 | 0 | 357 | 357 |
|  | Oct. 1, 1974 | 0 | 238 | 238 |
| Charley Creek, 15 mi S. Pomeroy | May 10, 1974 | 1 | 445 | 446 |
| 46°15'N. 117°30'W. | May 23, 1974 | 1 | 139 | 140 |
|  | May 30, 1974 | 0 | 95 | 95 |
|  | June 7, 1974 | 0 | 116 | 116 |
|  | Sept. 20, 1974 | 0 | 173 | 173 |
|  | Sept. 25, 1974 | 0 | 173 | 173 |
|  | Oct. 4, 1974 | 0 | 135 | 135 |
| *Elachertus argissa* (Walk.) (Hymenoptera: Eulophidae)[1] |  |  |  |  |
| Idaho: |  |  |  |  |
| 3.4 mi E. Bovill | Sept. 27, 1974 | 10 | 141 | 151 |
| 46°51'N. 116°20'W. | Oct. 9, 1974 | 3 | 74 | 77 |
|  | Oct. 18, 1974 | 12 | 51 | 63 |
| Montana: |  |  |  |  |
| 4 mi N. Evaro<br>47°05'N. 114°04'W. | Sept. 24, 1974 | 7 | 105 | 112 |
| Washington: |  |  |  |  |
| Colville Indian Reservation, E. Round Lake<br>48°17'N. 118°18'W. | Sept. 26, 1974 | 7 | 102 | 109 |
| Charley Creek, 15 mi S. Pomeroy | Sept. 20, 1974 | 8 | 81 | 89 |
| 46°15'N. 117°30'W. | Sept. 25, 1974 | 2 | 43 | 45 |
|  | Oct. 4, 1974 | 1 | 31 | 32 |
| *Dicladocerus japonicus* (Hymenoptera: Eulophidae)[5] |  |  |  |  |
| Idaho: |  |  |  |  |
| 3.4 mi E. Bovill<br>46°53'N. 116°20'W. | Sept. 27, 1974 | 0 | 65 | 65 |
| *Diadegma laricinella* (Strobl) (Hymenoptera: Ichneumonidae)[6] |  |  |  |  |
| Idaho: |  |  |  |  |
| 4.6 mi N. Troy<br>46°47' N. 116°48'W. | July 23, 1974 | 0 | 10 | 10 |

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[1] Parasite strain originated in Austria-northern Italy.
[2] Parasite strain originated in England.
[3] Parasite strain recolonized from Wisconsin.
[4] Parasite strain originated in Sweden.
[5] Adults reared from material collected in Japan.
[6] Adults reared from material collected in Austria-northern Italy.

Table A7.--*Releases of* Elachertus argissa, Necremnus metalarus, Chrysocharis laricinel
Dicladocerus westwoodii, *and* Dicladocerus japonicus *in Idaho, Montana, Washington, and Oregon 1975-76, and* Agathis pumila, *1971-76*

| Locality | Date released | Number released | | |
|---|---|---|---|---|
| | | Male | Female | Total |
| *Elachertus argissa* (Walker)[1] (Hymenoptera:Eulophidae) | | | | |
| Idaho: | | | | |
| Bob's Creek and Potlatch Creek | June 11, 1975 | 87 | 616 | 703 |
| 46°51'N 116°20'W, T41N R1E S33 | | | | |
| Meadow Creek | June 11, 1975 | 111 | 616 | 727 |
| 46°36'N 115°55'W, T38N R4E S11 | | | | |
| Felton Creek | June 20, 1975 | 84 | 616 | 700 |
| 46°48'N 116°50'W, T40N R4W S20 | Sept. 30, 1976 | 3 | 5 | 8 |
| 1 km N Troy Reservoir | June 20, 1975 | 50 | 200 | 250 |
| 46°49'N 116°47'W, T40N R4W S14 | | | | |
| Four Corners | May 21, 1976 | 30 | 123 | 153 |
| 48°17'N 116°59'W, T57N R5W S17 | | | | |
| Squaw Valley | May 21, 1976 | 25 | 124 | 149 |
| 48°27'N 116°56'W, T59W R5W S14 | Sept. 23, 1976 | 19 | 34 | 53 |
| Hanna Flats, 1 km W Priest Lake R.S. | May 21, 1976 | 30 | 123 | 153 |
| 48°34'N 116°56'W, T60N R5W S10 | | | | |
| Montana: | | | | |
| 6 km N Evaro | May 30, 1975 | 36 | 365 | 401 |
| 47°05'N 114°04'W, T15N R20W S1 | Sept. 27, 1976 | 11 | 34 | 45 |
| Washington: | | | | |
| Colville Indian Reservation, E Round Lake | May 28, 1975 | 35 | 357 | 392 |
| 48°17'N 118°18'W, T32N R36E S8 | Sept. 21, 1976 | 21 | 34 | 55 |
| Charley Creek, 26 km S Pomeroy | May 29, 1976 | 42 | 358 | 400 |
| 46°15'N 117°30'W, T 9N R42E S24 | | | | |
| Oregon: | | | | |
| 20 km N Elgin (BCC plot 6[2]) | May 28, 1975 | 11 | 105 | 116 |
| 45°44'N 117°55'W, T3N R39E S15 | Oct. 9, 1975 | 18 | 197 | 215 |
| | Oct. 10, 1975 | 21 | 125 | 146 |
| | Oct. 15, 1975 | 32 | 153 | 185 |
| 22 km NNE Elgin (BCC plot 5) | May 28, 1975 | 11 | 101 | 112 |
| 45°41'N 117°50'W, T3N R40E S9 | Sept. 18, 1975 | 11 | 21 | 32 |
| | Sept. 23, 1976 | 21 | 41 | 62 |
| 25 km NE Elgin (BCC plot 4) | May 28, 1975 | 7 | 88 | 95 |
| 45°42'N 117°40'W, T3N R41E S35 | | | | |
| 14 km SE Elgin (BCC plot 10) | Sept. 9, 1975 | 6 | 79 | 85 |
| 45°30'N 117°47'W, T1S R40E S11 | | | | |
| 13 km SE Elgin (BCC plot 9) | Sept. 9, 1975 | 9 | 84 | 93 |
| 45°29'N 117°50'W, T1S R40E S17 | | | | |
| 12 km SSE Elgin (BCC plot 8) | Sept. 9, 1975 | 11 | 76 | 87 |
| 45°28'N 117°51'W, T1S R40E S19 | | | | |
| 15 km SSE Elgin (BCC plot 7) | Sept. 9, 1975 | 10 | 79 | 89 |
| 45°26'N 117°52'W, T1S R39E S36 | | | | |

(continued next page; footnotes at end of tabl

Table A7. (continued)

| Locality | Date released | Number released |  |  |
|---|---|---|---|---|
|  |  | Male | Female | Total |
| *Necremnus metalarus* (Walker)[1] (Hymenoptera:Eulophidae) |  |  |  |  |
| Idaho: |  |  |  |  |
| Bob's Creek and Potlatch Creek | June 11, 1975 | 1 | 53 | 54 |
| 46°51'N 116°20'W, T41N R1E S33 | Sept. 25, 1975 | 7 | 487 | 494 |
| Meadow Creek | June 11, 1975 | 0 | 58 | 58 |
| 46°36'N 115°55'W, T38N R4E S11 | Sept. 26, 1975 | 14 | 485 | 499 |
| Felton Creek | June 20, 1975 | 0 | 54 | 54 |
| 46°48'N 116°50'W, T40N R4W S20 | Sept. 25, 1975 | 11 | 487 | 498 |
|  | Sept. 30, 1976 | 28 | 48 | 76 |
| Hanna Flats, 1 km W Priest Lake R.S. | Oct. 2, 1975 | 7 | 32 | 33 |
| 48°34'N 116°56'W, T60N R5W S10 | May 21, 1976 | 1 | 32 | 33 |
| Squaw Valley | Oct. 2, 1975 | 19 | 465 | 484 |
| 48°27'N 116°56'W, T59N R5W S14 | May 21, 1976 | 3 | 33 | 36 |
|  | Sept. 23, 1976 | 2 | 30 | 32 |
| Four Corners | Oct. 2, 1975 | 11 | 510 | 521 |
| 48°17'N 116°59'W, T57N R5W S17 | May 21, 1976 | 2 | 33 | 35 |
| Montana: |  |  |  |  |
| 6 km N Evaro | Sept. 26, 1975 | 2 | 363 | 365 |
| 47°05'N 114°04'W, T15N R20W S1 | Sept. 27, 1976 | 2 | 33 | 35 |
| Washington: |  |  |  |  |
| Colville Indian Reservation, E Round Lake | Sept. 24, 1975 | 2 | 326 | 328 |
| 48°17'N 118°18'W, T32N R36E S8 | Sept. 21, 1976 | 1 | 33 | 34 |
| Charley Creek, 26 km S. Pomeroy | Sept. 20, 1975 | 8 | 564 | 572 |
| 46°15'N 117°30'W, T9N R42E S24 |  |  |  |  |
| Oregon: |  |  |  |  |
| 20 km N Elgin (BCC plot 6) | May 28, 1975 | 2 | 36 | 38 |
| 45°45'N 117°55'W, T3N R39E S15 | Oct. 9, 1975 | 0 | 331 | 331 |
|  | Oct. 10, 1975 | 0 | 56 | 56 |
|  | Oct. 15, 1975 | 0 | 76 | 76 |
| 22 km NNE Elgin (BCC plot 5) | May 28, 1975 | 3 | 36 | 39 |
| 45°45'N 117°50'W, T3N R40E S9 | Sept. 18, 1975 | 3 | 124 | 127 |
|  | Sept. 23, 1975 | 2 | 307 | 309 |
|  | Sept. 29, 1975 | 9 | 521 | 530 |
|  | Oct. 2, 1975 | 18 | 873 | 891 |
|  | May 30, 1976 | 0 | 42 | 42 |
|  | Sept. 23, 1976 | 27 | 50 | 77 |
| 25 km NE Elgin (BCC plot 4) | May 28, 1975 | 6 | 34 | 40 |
| 45°42'N 117°40'W, T3N R41E S35 |  |  |  |  |
| 14 km SE Elgin (BCC plot 10) | Sept. 9, 1975 | 5 | 64 | 69 |
| 45°30'N 117°47'W, T1S R40E S11 |  |  |  |  |
| 13 km SE Elgin (BCC plot 9) | Sept. 9, 1975 | 7 | 57 | 64 |
| 45°29'N 117°50'W, T1S R40E S17 |  |  |  |  |
| 12 km SSE Elgin (BCC plot 8) | Sept. 9, 1975 | 10 | 58 | 68 |
| 45°28'N 117°51'W, T1S R40E S19 |  |  |  |  |
| 15 km SSE Elgin (BCC plot 7) | Sept. 9, 1975 | 7 | 59 | 66 |
| 45°26'N 117°52'W, T1S R39E S36 |  |  |  |  |

(continued next page; footnotes at end of table)

Table A7. (continued)

| Locality | Date released | Number released |  |  |
|---|---|---|---|---|
|  |  | Male | Female | Total |
| *Chrysocharis laricinellae* (Ratz.) (Hymenoptera:Eulophidae) |  |  |  |  |
| Idaho:[1] |  |  |  |  |
| Four Corners | Sept. 23, 1976 | 85 | 26 | 111 |
| 48°17'N 116°59'W, T57N R5W S17 |  |  |  |  |
| Squaw Valley | Sept. 23, 1976 | 85 | 26 | 111 |
| 48°27'N 116°56'W, T59N R5W S14 |  |  |  |  |
| Hanna Flats, 1 km W Priest Lake R.S. | Sept. 23, 1976 | 85 | 26 | 111 |
| 48°34'N 116°56'W, T60N R5W S10 |  |  |  |  |
| Felton Creek | Sept. 30, 1976 | 200 | 74 | 274 |
| 46°48'N 116°50'W, T40N R4W S20 |  |  |  |  |
| Oregon:[3] |  |  |  |  |
| 26 km NE Elgin (BCC plot 3) | May 28, 1975 | 491 | 307 | 798 |
| 45°42'N 117°39'W, T3N R41E S35 | June 4, 1975 | 524 | 488 | 1,012 |
|  | Sept. 23, 1975 | 284 | 124 | 408 |
| 22 km NNE Elgin (BCC plot 5) | May 19, 1976 | 368 | 328 | 696 |
| 45°41'N 117°50'W, T3N R40E S9 | Sept. 23, 1976 | 342 | 145 | 487 |
|  | Sept. 29, 1976 | 393 | 74 | 467 |
|  | Oct. 7, 1976 | 268 | 69 | 337 |
| *Dicladocerus westwoodii* Westw.[1] (Hymenoptera:Eulophidae) |  |  |  |  |
| Idaho: |  |  |  |  |
| Benton Creek, Priest River Exp. For. | May 20, 1976 | 117 | 46 | 163 |
| 48°21'N 116°50'W, T58N R4W S26 | Sept. 22, 1976 | 105 | 39 | 144 |
|  | Oct. 8, 1976 | 278 | 155 | 433 |
| *Dicladocerus japonicus* Yoshimoto[4] (Hymenoptera:Eulophidae) |  |  |  |  |
| Idaho: |  |  |  |  |
| 1 km N Troy Reservoir | June 20, 1975 | 258 | 285 | 543 |
| 46°49'N 116°48'W, T40N R4W S14 |  |  |  |  |
| Four Corners | May 21, 1976 | 52 | 40 | 92 |
| 48°17'N 116°59'W, T57N R5W S17 |  |  |  |  |
| Hanna Flats, 1 km W Priest Lake R.S. | May 21, 1976 | 52 | 40 | 92 |
| 48°34'N 116°56'W, T60N R5W S10 |  |  |  |  |
| Squaw Valley | May 21, 1976 | 53 | 41 | 94 |
| 48°27'N 116°56'W, T59N R5W S14 |  |  |  |  |
| Moscow Mt., 7 km N Troy | June 4, 1976 | 34 | 54 | 88 |
| 46°47'N 116°48'W, T40N R4W S23 |  |  |  |  |
| Oregon: |  |  |  |  |
| 22 km NNE Elgin (BCC plot 5) | May 30, 1976 | 78 | 102 | 180 |
| 45°45'N 117°50'W, T3N R40E S9 | Sept. 23, 1976 | 72 | 280 | 352 |
|  | Oct. 7, 1976 | 237 | 146 | 383 |

(continued next page; footnotes at end of table

Table A7. (continued)

| Locality | Date released | Number released | | |
|---|---|---|---|---|
| | | Male | Female | Total |
| *Agathis pumila* (Ratz.) (Hymenoptera:Braconidae) | | | | |
| Washington: | | | | |
| Charley Creek, 26 km S Pomeroy | July 10, 1971[5] | 73 | 14 | 87 |
| 46°15'N 117°30'W, T9N R42E S24 | July 19, 1971[5] | 31 | 122 | 153 |
| | July 7, 1973[1] | 91 | 111 | 202 |
| | July 7, 1973[6] | 131 | 222 | 353 |
| Oregon: | | | | |
| Emigrant Springs, 27 km ESE Pendleton[5] | July 12, 1971 | 85 | 14 | 99 |
| 45°33'N 118°28'W, T1N R35E S20 | July 19, 1971 | 38 | 113 | 151 |
| | July 20, 1972 | 30 | 38 | 68 |
| | July 14, 1973 | 341 | 333 | 674 |
| | July 20, 1973 | 10 | 106 | 116 |
| Hwy 204, 14 km E Weston | Aug. 20, 1974[6] | 34 | 21 | 55 |
| 48°48'N 118°14'W, T4N R37E S30 | Aug. 28, 1974[6] | 10 | 7 | 17 |
| | July 7, 1975[1] | 340 | 222 | 562 |
| | July 14, 1975[1] | 11 | 74 | 85 |
| 26 km NE Elgin (BCC plot 3)[5] | Aug. 20, 1975 | 24 | 300 | 324 |
| 45°42'N 117°39'W, T3N R41E S35 | Aug. 25, 1975 | 6 | 300 | 306 |
| 25 km NE Elgin (BCC plot 4)[5] | Aug. 20, 1975 | 24 | 300 | 324 |
| 45°42'N 117°40'W, T3N R41E S35 | Aug. 25, 1975 | 8 | 400 | 408 |
| 22 km NNE Elgin (BCC plot 5) | Aug. 20, 1975[5] | 24 | 300 | 324 |
| 45°45'N 117°50'W, T3N R40E S9 | Aug. 21, 1975[5] | 15 | 300 | 315 |
| | Aug. 25, 1975[5] | 4 | 200 | 204 |
| | July 6, 1976[1] | 40 | 87 | 127 |
| 20 km N Elgin (BCC plot 6)[5] | Aug. 21, 1975 | 15 | 300 | 315 |
| 45°44'N 117°55'W, T3N R39E S15 | Aug. 25, 1975 | 6 | 300 | 306 |
| 15 km SSE Elgin (BCC plot 7)[5] | July 29, 1975 | 66 | 141 | 207 |
| 45°26'N 117°52'W, T1S R39E S36 | Aug. 21, 1975 | 24 | 300 | 324 |
| | Aug. 22, 1975 | 6 | 300 | 306 |
| | Aug. 26, 1975 | 1 | 200 | 201 |
| | Aug. 27, 1975 | 0 | 4 | 4 |
| 12 km SSE Elgin (BCC plot 8)[5] | Aug. 15, 1975 | 100 | 100 | 200 |
| 48°28'N 117°51'W, T1S R40E S19 | Aug. 20, 1975 | 24 | 300 | 324 |
| | Aug. 22, 1975 | 6 | 300 | 306 |
| | Aug. 26, 1975 | 0 | 100 | 100 |
| | July 4, 1976 | 1 | 10 | 11 |
| | July 6, 1976 | 30 | 30 | 60 |
| | July 8, 1976 | 100 | 100 | 200 |
| | July 12, 1976 | 20 | 80 | 100 |
| | July 14, 1976 | 40 | 200 | 240 |
| | July 19, 1976 | 0 | 106 | 106 |
| 13 km SE Elgin (BCC plot 9)[5] | Aug. 20, 1975 | 24 | 300 | 324 |
| 45°29'N 117°50'W, T1S R40E S17 | Aug. 22, 1975 | 6 | 300 | 306 |
| | Aug. 26, 1975 | 2 | 100 | 102 |
| | Aug. 28, 1975 | 0 | 52 | 52 |
| | July 12, 1976 | 75 | 300 | 375 |
| | July 16, 1976 | 10 | 122 | 132 |
| 14 km SE Elgin (BCC plot 10)[5] | Aug. 20, 1975 | 24 | 300 | 324 |
| 45°30'N 117°47'W, T1S R40E S11 | Aug. 21, 1975 | 15 | 300 | 315 |
| | Aug. 22, 1975 | 6 | 300 | 306 |

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[1] Parasite strain originated in Austria-northern Italy.
[2] Boise Cascade Corporation plot number.
[3] Parasite strain originated in Sweden.
[4] Parasite strain originated in Japan.
[5] Parasite strain recolonized from Idaho-Montana.
[6] Parasite strain recolonized from Wisconsin.

Table A8.--*Larch casebearer phenology and bird activity at Coram Experimental Forest, Montana*[1]

| Season | Instar or stage | Biological phase | Month | Dates (approx.) | Location | Activity | Duration | Vulnerability to birds (estimate) | Bird seasonal activities |
|---|---|---|---|---|---|---|---|---|---|
| Spring | IV | Larvae in case | Mid-April<br>Late May | Apr. 15-<br>May 25 | In case out on needle tips | Feeding on developing needles | 4-6 weeks | High - larvae are mobile | Winter residents. Spring migrants arrive. Territory established. |
|  | Pupae | Pupate | Late May-<br>Mid-June | May 25-<br>June 15 | Center of needle fascicle | Quiescent | 3 weeks | Medium - requires search | Nesting |
| Summer | Breeding adult | Moth | Mid-June-<br>Early July | June 15-<br>July 10 | On branches in in canopy (weak fliers) | Laying eggs and sitting on needles, flying | 3 weeks± | High? Much other insect food available | Fledglings |
|  | Egg | Egg-Larvae | Mid-June<br>Early July | June 15-<br>July 10 | Egg on needle; larva inside needle | Mines into needle and feeds | 2-4 weeks | Little or none. Inconspicuous | Dispersal |
|  | I-II | Larvae | Early July<br>Early Sept. | July 10-<br>Sept. 10 | Inside needle | Feeding inside needle | 8 weeks | Little or none | Flocking |
| Fall | III | Larvae in case | Early Sept.<br>Late Oct. | Sept. 10-<br>Oct. 25 | Out on needle | Feeding until needles turn yellow | 6-7 weeks | High, if birds are interested | Migration |
| Winter | III | Larvae in case | Late Oct.<br>Mid-Apr. | Oct. 25-<br>Apr. 15 | Attached to twig at base of fascicle | Hibernating | 6 months-overwinter | High if birds present | Winter residents. |

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[1] Based on Denton, R. E. 1965. Larch casebearer in western larch forests. USDA For. Serv., For. Pest Leafl. 96, 6 p.; and personal communication with author.

[2] At Coram elevations from 3,300 ft (1,006.5 m) to about 4,200 ft (1,281 m).

Denton, Robert E.
1979. Larch casebearer in western larch forests. USDA For. Serv. Gen. Tech. Rep. INT-55, 62 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

The larch casebearer was discovered in western larch forests in Idaho in 1957 and now infests most of the botanical range of its host species. Damage consists mainly of severely reduced growth in increment, although tree mortality has occurred when infestations have persisted for more than 5 years. Abundant information is related about biological control of the casebearer by introducing exotic parasites.

KEYWORDS: Coleophoridae (-forest damage), population sampling, host tree impacts, biological control, chemical control.

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KEYWORDS: Coleophoridae (-forest damage), population sampling, host tree impacts, biological control, chemical control.

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# SPOT FIRE DISTANCE FROM BURNING TREES — A PREDICTIVE MODEL

FRANK A. ALBINI

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# SPOT FIRE DISTANCE FROM BURNING TREES — A PREDICTIVE MODEL

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All of these people are located at the Intermountain Station's Northern Forest Fire Laboratory in Missoula, Montana.

# RESEARCH SUMMARY

This paper presents a predictive model for calculating the maximum spot fire distance to be expected when firebrands are thrown into the air by the burning of tree crowns either individually or in small groups. Variables included in the model are the quantity and surface/volume ratio of foliage in the burning tree(s), the height of the tree(s), and the wind field that transports the firebrands, and the firebrand burning rate. Many aspects of the processes modeled are as yet incompletely understood and so are only weakly represented. Improved models are needed for all of the processes before predictions can be made with certainty, but a step-by-step, graphical procedure is presented here for test and evaluation in the field. No validation data are available at present.

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# INTRODUCTION

In the jargon of forest fire control a "spot fire" is a fire set outside the perimeter of the main fire by flying sparks or embers (USDA Forest Service 1956). A wildland fire is said to be "spotting" when it produces sparks or embers that are carried by the wind and start new fires beyond the zone of direct ignition by the main fire. This type of fire spread occurs with increasing frequency as fuel moisture content declines (table 1).

Fire spread by spotting is a chance event. When it will occur and over what distance are at present unpredictable quantities that complicate the task of wildfire control. And fires ignited for desirable effects under prescribed conditions sometimes escape their intended boundaries because of spotting.

This vexing phenomenon has long challenged both the research community and fire management practitioners. This paper presents a theoretical framework and instructional materials for predicting the maximum spot fire distance from burning trees. With testing and refinement, the model given here should enable researchers and managers alike to better understand and cope with spot fires.

## Problem Description

Spotting occurs over a wide range of distances, depending upon windspeed and the type (and quantity) of fuel involved in the main fire as well as fuel moisture. The severity of a potential spotting problem can be described numerically by the maximum spot fire distance to be anticipated under the conditions in question. The problem addressed in this paper arises under conditions of intermediate fire severity in which spotting distances up to a mile or two might be encountered. These burning conditions represent a rough upper limit to fire severity under which prescribed burning might be carried out. In some cases an estimate of maximum possible spotting distance may assist in delimiting prescription regimes. Large wildfires also occur frequently under burning conditions that admit intermediate-range spotting. This situation arises when fire intensity is not so high as to cause extensive crowning or crown fire spread (Van Wagner 1977), but when the intensity is sufficiently high that the fire cannot be "trusted" to burn only surface fuels (table 1).

Situations *not considered* in this work are those extreme cases in which spotting may occur up to tens of miles from the main front, as in running crown fires, fires in heavy slash or chaparral under extreme winds, and fires in which fire whirls loft burning material high into the air.

The situation treated here starts with the assumption that there occurs the occasional or sporadic "torching out" of individual trees or small groups of trees. These singular events provide the mechanism for the lofting of firebrands that are then carried by the prevailing wind. While this is not the most severe case of spread by spotting, it is a situation that often confronts planners in fire suppression and fire prescription work.

A method is sought that will permit prediction of the maximum spot fire distance to be anticipated from burning trees, given a knowledge of the terrain, forest cover, and windspeed. If maximum spotting distance can be predicted, the information might be useful in prescription writing, selecting fire control line placement, positioning of "spot chasers," and similar matters that fire managers must deal with.

Table 1.--*Spotting potential related to fuel moisture content*

(This table is based on data compiled by Hal E. Anderson, USDA Forest Service, Intermountain Forest and Range Experiment Station, Northern Forest Fire Laboratory, for Fire Behavior Officer training (National Interagency Fire Training Center, Marana Air Park, Arizona).)

| Fuel moisture content | | | Relative ease of chance ignition, likelihood of spotting, general burning conditions |
|---|---|---|---|
| Relative humidity* | 1/2-inch fuel stick | Forest litter | |
| - - - - - - | Percent - - - | - - - | |
| | | >25 | Little or no ignition[1] |
| >60 | >15 | >20 | Very little ignition;[2] some spotting may occur with winds above 9 mi/h[3] |
| 45-60 | 12-15 | 15-19 | Low ignition hazard - campfires become dangerous;[1] glowing brands cause ignition when relative humidity <50 percent[3] |
| 40+<br>30-45 | 7-12 | 11-14 | Medium ignitibility - matches become dangerous;[1] "easy" burning conditions[4] |
| 26-40 | | 8-10 | High ignition hazard - matches always dangerous;[1] occasional crowning, spotting caused by gusty winds;[2] "moderate" burning conditions[4] |
| 15-30 | 5-7 | 5-7 | Quick ignition, rapid buildup, extensive crowning; any increase in wind causes increased spotting, crowning, loss of control;[2] fire moves up bark of trees igniting aerial fuels; long distance spotting in pine stands;[3] dangerous burning conditions[4] |
| <15 | <5 | <5 | All sources of ignition dangerous;[1] aggressive burning, spot fires occur often and spread rapidly, extreme fire behavior probable;[2] critical burning conditions[4] |

*Relative humidity is a surrogate for "fine" fuel moisture content.

[1] Gisborne (1936)
[2] USDA Forest Serv., Northern Region (1973)
[3] Florida Div. For. (1973)
[4] Barrows (1951)

## Approach to Solution

The approach used in constructing this model is to examine each phase of the process and develop a mathematical description for it. The individual "submodels" are based on physical principles to a large extent, but assumptions, approximations, and inadequately supported empirical relationships are sprinkled throughout. Each submodel provides an element of information needed to predict the maximum spot fire distance. As better theories and data become available, the submodels can be revised and improved. But the framework that links each of the submodels rests on a series of basic assumptions that form a conceptual picture of the overall process. The process modeled is the following sequence:

A tree, or a small group of trees, "torches out." The flame, and the buoyant plume above it, exist for a brief period of time. This fluid flow field is capable of lofting potential firebrands into the air. The flow structures are described by separate, steady-state models, joined at the tip of the flame. These models assume still ambient air for simplicity, and to ensure that a maximum height is predicted for the firebrand particles.

The flight of an inert wood cylinder in the flame/plume flow field serves to predict the height of a potential firebrand as a function of time. The particle is assumed to start from the top of a tree involved in the flame at the instant the flame is established. It travels vertically until the flame goes out and the flow field collapses. The height achieved by the particle depends on its diameter and density and on the flow field description.

When the particle reaches its maximum height, it is then subjected to the ambient wind field and transported laterally as it falls. The burning of the particle is accounted for by a simple empirical model that describes its falling velocity as a function of time. The maximum spot fire distance is established by requiring that the particle is totally consumed just as it returns to the ground. Smaller particles would travel farther but burn out before reaching the ground; larger ones could not travel so far.

The wind field that carries the firebrand can be modeled by a logarithmic variation with height for flat terrain (fig. 1). But another submodel is required to reflect the influence of ridges and valleys on the wind field (fig. 2).

Each of the submodels is discussed more fully in the section entitled Synopsis of Submodel Content (p. 19) and is described in appendixes A-F.

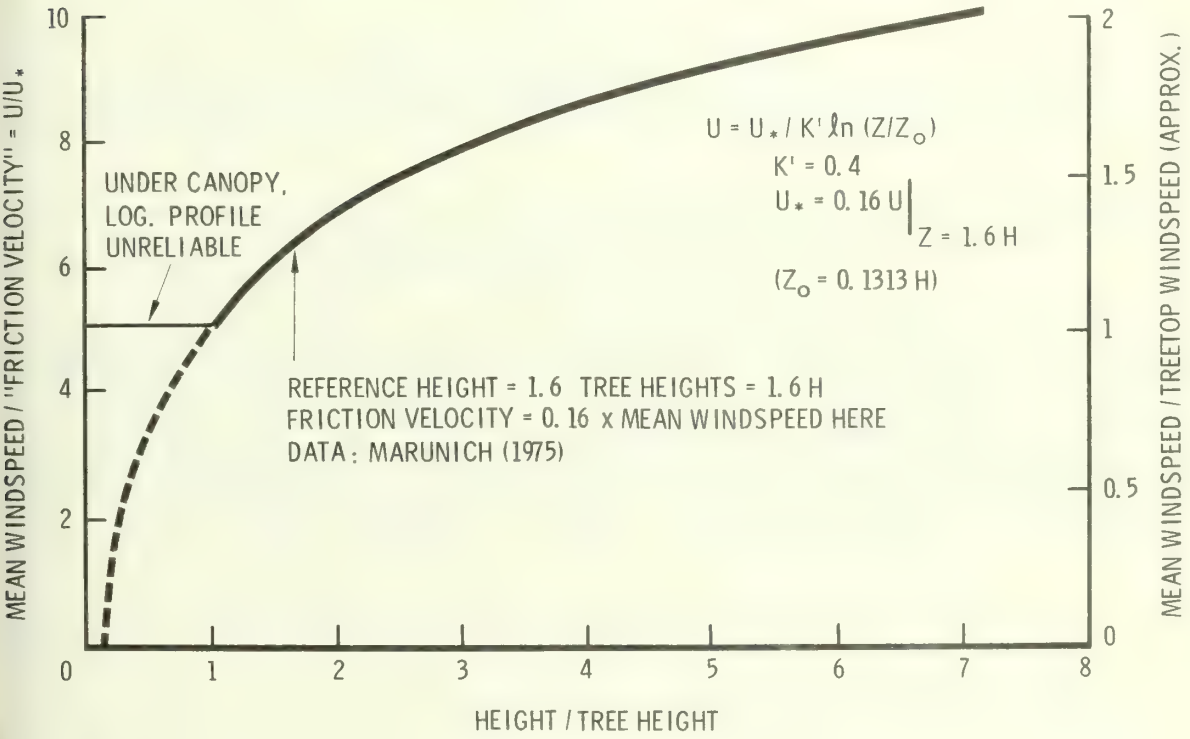

*Figure 1.--Logarithmic windspeed variation with height (above uniform forest canopy).*

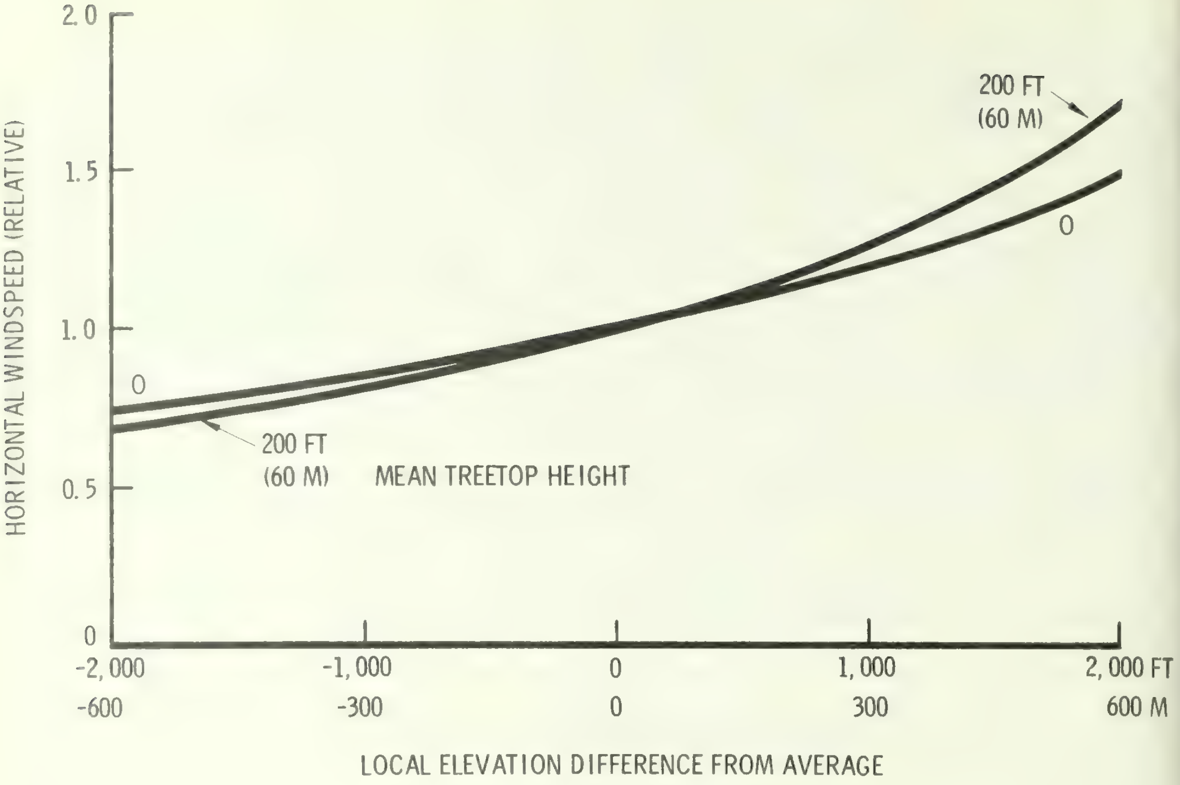

*Figure 2.--Variation of horizontal windspeed (at constant height above local terrain) with elevation difference from average.*

## Factors Omitted in this Approach

Before this model can be applied and tested, it is essential that the user recognize what the model does not include. Several essential features of the spotting process are omitted from consideration here and no amount of adjustment of the submodels will allow them to be reflected in the results. These are factors that must be incorporated by further model development. Until this is accomplished, the user must supply the missing pieces by whatever means he can. The principal missing elements are:

1. *The likelihood of trees burning.* No consideration is included here of the probability that a tree (or group of trees) will "torch out." The type and quantity of surface fuels, the burning conditions, overstory species, crown separation, etc., all influence this factor. The model presented here must be thought of as a "what if" computation aid; the user must supply the description of the trees that are to be considered to burn as input to the model. Van Wagner (1977) describes conditions for the start and spread of crown fires. When burning conditions are so severe that crown fires are to be expected, this model would be of only marginal interest. So Van Wagner's work can be used as a guide to conditions under which one should consider the chance of torching and spotting to be significant.

2. *Availability of optimum firebrand material.* This model presumes that at east one ideally suited firebrand particle exists in an unfettered state near the op of a burning tree. This is consistent with the intention to estimate the maxi- um potential spot fire distance only. Any reduction in maximum spotting distance ue to the fact that an ideal particle was not present is outside the scope of the odel presented here. The fact that a wood cylinder is used to represent the maxi- um-range firebrand is not felt to be a source of significant distortion. This as- umption is discussed more fully below.

3. *The probability of spot fire ignition.* In this model the maximum-range article is idealized as just being totally consumed at the instant it reaches the round. The fact that an extremely small spark or ember can indeed ignite forest uels is established by experimental data,[1] so this idealization does not substan- ially weaken the model. But a firebrand must come into contact with easily ig- ited dry fuel (e.g., litter, duff, rotten wood) for a spot fire to start. This odel does not deal with the chance of such contact or the probability that ignition ill occur if the contact is made. Here we present only the distance that a fire- rand can travel and still retain the possibility of starting a fire.

4. *The number of spot fires.* The probabilistic question of how many spot ires there might be under certain conditions, or the number per unit surface area, s not addressed here. Only when the three elements listed above are appropriately odeled will it be possible to predict the density distribution of spot fire igni- ions (Muraszew and Fedele 1976).

# ESTIMATING MAXIMUM SPOT FIRE DISTANCE

This section gives a step-by-step procedure for estimating maximum spot fire stance from a tree (or group of trees) that "torches out." The steps are numbered correspond with the specimen worksheet (exhibit 1, p. 8).

1. First, record the species of tree assumed to burn, the diameter at breast ight (d.b.h.) and height of the tree, and the number of trees assumed to burn multaneously.

These data will be needed during the completion of the worksheet, and it is im- rtant that the investigator "leave some tracks" so the work can be checked or con- tinued after interruption. Be sure to cross out the incorrect or circle the correct its of measurement when recording dimensional data. With few exceptions one is st advised to retain one system of units for each worksheet used.

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[1] R. A. Wilson, Jr., and A. P. Brackebusch, personal communication of unpublished ta; Northern Forest Fire Laboratory, Missoula, Mont., September 1977.

2. Consult the guide in table 2 and select from figures 3-5 the curves to use.[2] Read from the appropriate curves the steady flame height and steady flame duration for a single burning tree of the size and species of interest. Record these on the worksheet. These numbers must be revised if more than a single tree is involved in producing the flame.

3. Consult figure 6 and record the multiplying factors for flame height and duration. Note that the flame height multiplier is greater than unity and the duration factor is less than unity, so these numbers should not be confused. Carry out the indicated multiplications and record the results. It is not necessary to record more than two significant figures. For example, a duration calculated to be 3.622 should be recorded as 3.6; a flame height of 129.4 should be recorded as 130.

4. Divide the height of the burning tree (or the average height of the burning group of trees) by the adjusted flame height determined in step 3. Be sure to use the same units of measurement so the ratio will be dimensionless. Record the result and use it to select the proper curve in figure 7. The dimensionless flame duration derived in step 3 is used to enter figure 7; read the appropriate curve and record the lofted firebrand height/steady flame height value. Multiply this quantity by the adjusted steady flame height from step 3 and record the result. To this result add one-half the tree height to obtain the initial firebrand height above ground. This result is used in figure 8 (step 6).

5. The graphs for calculating spotting distance use the windspeed at treetop height at the average elevation (e.g., midslope elevation for a ridge-valley system). It is often necessary to adjust the available data on windspeed to infer this value. First, record for reference the elevation and height above terrain at the spot the windspeed value is known or estimated. Record also this reference windspeed, the average elevation, and the mean treetop height in the area downwind of the firebrand source. This mean treetop height is intended to characterize the general forest cover of the terrain as it influences the wind field that will transport a firebrand. If the area has broken forest cover, use half the treetop height of the forest-covered portion.

Subtract the average terrain elevation from the elevation where the wind was measured. Use this difference in figure 2 to estimate the ratio of windspeed at the observation point to that at the average elevation. Record this value in the blank space marked X on the worksheet.

Next, a correction may be needed for the height above the vegetation at which the reference windspeed was determined. The reference windspeed should be reduced if it was measured above the canopy top represented by the mean treetop height noted above. If so, divide the windspeed measurement height by the mean treetop height and obtain from figure 1 the windspeed ratio. Record this value in the blank space marked Y.

---

[2] Figures are given for three regions: Intermountain west, north central/northeast, and south/southeast. The literature revealed no foliage weights for west/northwest tree species. Intermountain species might serve as adequate substitutes, such as grand fir for noble, red, and Pacific silver firs, subalpine fir for white fir, western white pine for sugar pine and Monterey pine, and Ponderosa pine for Jeffrey, Coulter, and Digger pine. Species that are essentially the same, such as Ponderosa pine, Douglas-fir, or lodgepole pine, should be directly substituted until more data become available.

If the windspeed reference height is not greater than the mean treetop height, then this correction is not to be made using figure 1. Because no generally accepted procedure is known to the author for correcting windspeed measurements *upward* to treetop height, the following suggestions are offered only as interim measures and are not based upon accepted theory or specific data.[3]

| *Windspeed Measurement Site* | *Y Value Suggested* |
|---|---|
| Open ridgetop, 20-foot anemometer tower | 1.0 |
| Open ridgetop, hand-held anemometer | .5 |
| Forest opening, 20-foot anemometer tower | .5 |
| Forest opening, hand-held anemometer | .4 |
| Under canopy, hand-held anemometer | .3 |

Apply the corrections for elevation (X) and height above terrain (Y) by using hese factors as divisors of the reference windspeed value. Enter the adjusted indspeed value on the worksheet. This is used in the next step.

6. Figure 8 is a nomograph allowing one to predict maximum spot fire distance ver flat terrain with a uniform forest cover. This distance can be corrected for he effects of terrain on the wind field, so must be computed even if the terrain is ot approximately flat. Two versions of figure 8 are given--8A for British units f measurement and 8B for metric units. Choose the appropriate version of the igure and proceed as follows:

a. Enter the graph on the firebrand initial height scale (from step 4), drawing vertical line up to the curve labeled with the treetop height recorded in step 5.

b. From the intersection point (interpolated as necessary) draw a horizontal ine into the left-hand panel, through to the curve labeled with the windspeed de- ermined in step 5.

c. From the intersection point (interpolated as necessary) draw a vertical ine down to the left horizontal scale. There read off the maximum spot fire dis- ance and record on the worksheet.

The dashed lines on the figure illustrate these steps.

7. If the terrain over which the firebrand would fly has a substantial varia- ion in elevation, the flat-terrain spot distance can be corrected by the use of the raphs in figure 9. First, determine which description best fits the location of e firebrand source: midslope on the leeward side of a ridge (figure 9A), the lley floor (figure 9B), midslope on the windward side of a ridge (figure 9C), or dgetop (figure 9D). Next, record the elevation difference from ridgetop to valley ttom and the distance from ridgeline to valley bottom as would be shown on a map. vide the flat terrain spot distance from step 6 by the ridge-to-valley distance d record the result. Use this quantity in the appropriate version of figure 9 determine the ratio of spotting distance in sinusoidal terrain to that over flat rrain. Multiply this number by the flat-terrain spotting distance from step 6 d record the result. This result is the maximum spot fire distance as would be own on a map.

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[3] Albini, F. A. and R. G. Baughman. Estimating windspeeds for predicting wildland fe behavior. USDA For. Serv. Res. Paper INT-211, 12 p. Intermt. For. and Range E. Stn., Ogden, Utah.

WORKSHEET FOR ESTIMATING MAXIMUM SPOT FIRE DISTANCE

1. Describe tree(s) assumed to torch out.

Species____________________ DBH____(cm-in) Height_____(m-ft) Number simultaneous_____
↑ (use in step 2) ↑ (use in step 4)↑ (use in step 3, fig 6)↑
See table II for number of figure to use in step 2.

2. The steady flame from one burning tree.

From fig (3A-4A-5A): Flame height_______(m-ft). From fig (3B-4B-5B): Duration_____

3. From fig 6: Flame height multiplier______. From fig 6: Flame duration multiplier_____

Adjusted values: steady flame height_______(m-ft). Steady flame duration_____
(use in step 4) ↑ (use in step 4, fig 7)↑

4. Tree height (step 1) ÷ Adjusted steady flame height (step 3) = ________(use in fig 7)

From fig 7: Lofted firebrand height/steady flame height_________.

Multiply by adjusted steady flame height (step 3). Result: ____________(m-ft)

Add 1/2 tree height (recorded in step 1). Result: ___________(m-ft)(use in step 6, fig 8)

5. Windspeed adjustments. Record for reference:

At elevation _____________(m-ft) at height_____(m-ft) windspeed is______(km/h-mi/h)

Avg. elevation_____________(m-ft). Mean treetop height along firebrand path_________(m-ft)

Difference = _____________(m-ft) (use in fig 2) (use in fig 2 and step 6, fig 8)↑

From fig 2: windspeed relative to value at same height but at avg. elevation__________(X)

Windspeed reference height ÷ mean treetop height = ________(use in fig 1 if greater than 1)

See instructions for step 5 (use of fig 1 may not be indicated)

From fig 1, or by estimate, windspeed at reference height relative to treetop__________(Y)

Divide reference windspeed by (X) and result by (Y). Result_____________(km/h-mi/h)
(use in fig 8)↑

6. From fig 8(A-B): Maximum spot distance over flat terrain________________(km-mi)

7. Correct for terrain relief along flight path if necessary.
Firebrand source is located nearest to:

Leeward midslope_____ valley floor_____ windward midslope_____ ridgetop_____
Use fig no: 9A 9B 9C 9D

Elevation difference from ridge to valley______________(m-ft)

Distance from ridge to valley as would be shown on map__________(km-mi)

Spot distance from step 6 ÷ ridge-to-valley distance = ____________(use in fig 9)

From fig 9(A-B-C-D): Spot distance in sinusoidal terrain/flat terrain distance__________

Multiply by maximum spot distance over flat terrain (step 6).

Result:____________________km-mi)
This is the maximum spot distance (as shown on map) estimate ↑

EXHIBIT 1. SPECIMEN WORKSHEET

Table 2.--*Data source list and key to figures for obtaining steady flame height and duration for a single burning tree*

| Region | Tree species | Data source (Foliage weight) | Figures | Curve |
|---|---|---|---|---|
| INTERMOUNTAIN WEST | | Brown 1977 | 3A, 3B | |
| | Douglas-fir | | | DF |
| | Engelmann spruce | | | ES |
| | Grand fir | | | GF |
| | Lodgepole pine | | | LP |
| | Ponderosa pine | | | PP |
| | Subalpine fir | | | AF |
| | Western hemlock | | | WH |
| | Western red cedar | | | WRC |
| | Western white pine | | | WP |
| NORTH CENTRAL/NORTHEAST | | | 4A, 4B | |
| | Balsam fir | Baskerville 1965A | | BF |
| | Black spruce | Weetman and Harland 1964 | | BS |
| | Jack pine | Brown 1965 | | JP |
| | Red pine (North Cent.) | Brown 1965 | | RPC |
| | Red pine (Northeast) | Kittredge 1944 | | RPE |
| | Scots Pine | Ovington and Madgwick 1959 | | SP |
| | White spruce | Baskerville 1965B | | WS |
| SOUTH/SOUTHEAST | | | 5A, 5B | |
| | Loblolly pine | Rogerson 1964 | | LBP |
| | Longleaf pine | Taras and Clark 1977[1] | | LLP |
| | Pond pine | Wendell 1960 | | PP |
| | Shortleaf pine | Loomis and others 1966 | | SLP |
| | Slash pine | Johansen and McNab 1977 | | SP |

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[1] The relationship reported by Taras and Clark requires tree height as well as diameter at breast height. Tree height was approximated by a regression of data on shortleaf pine reported by Clark and Taras (1976).

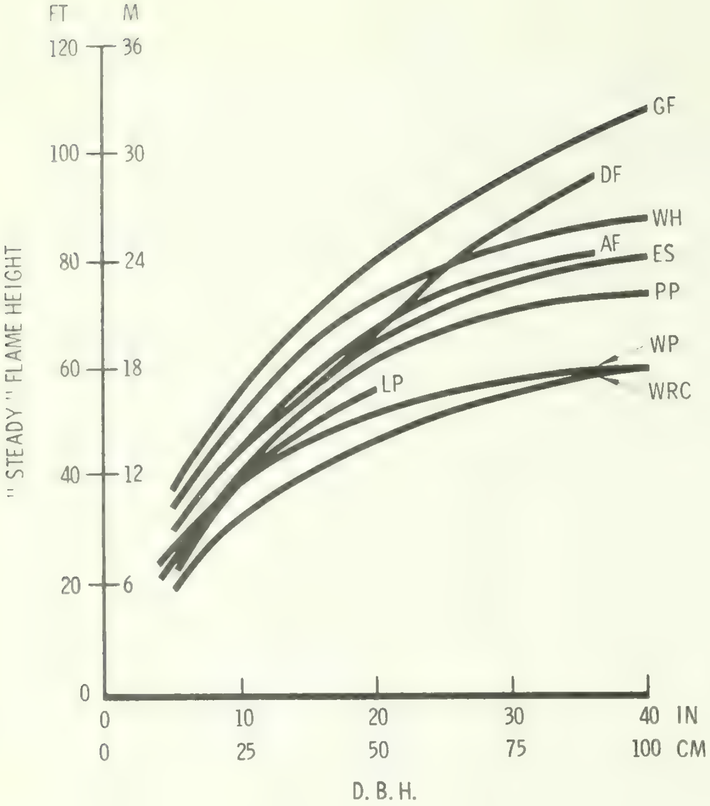


*Figure 3a.--Height of "steady" flame from burning of one tree corwn in still air, for several species of trees common to the intermountain area, Western U.S.A.*

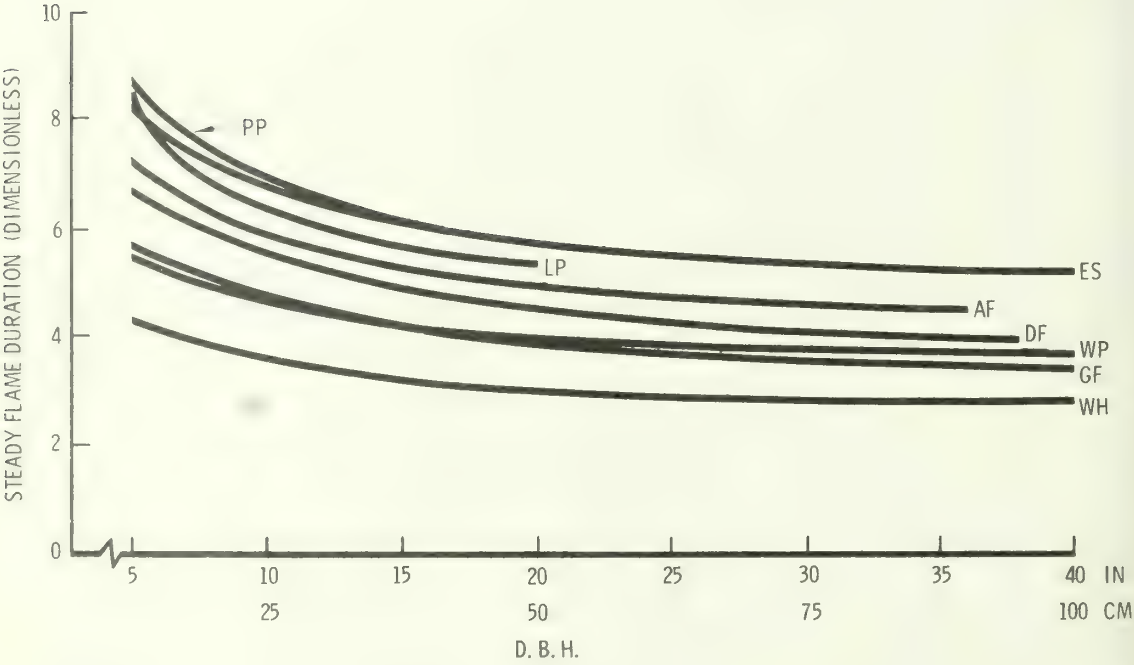
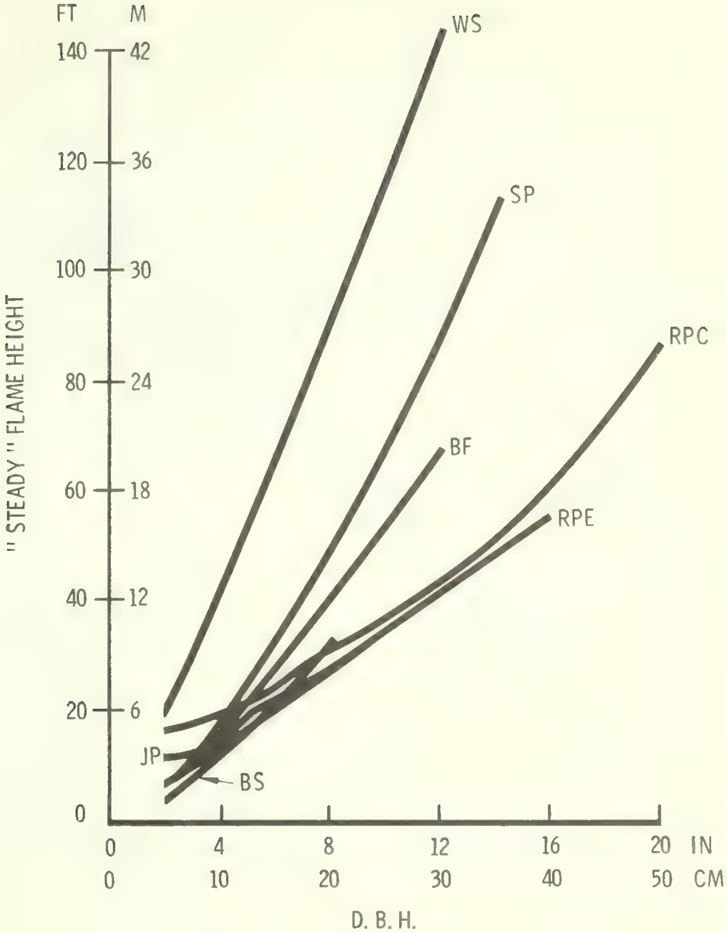
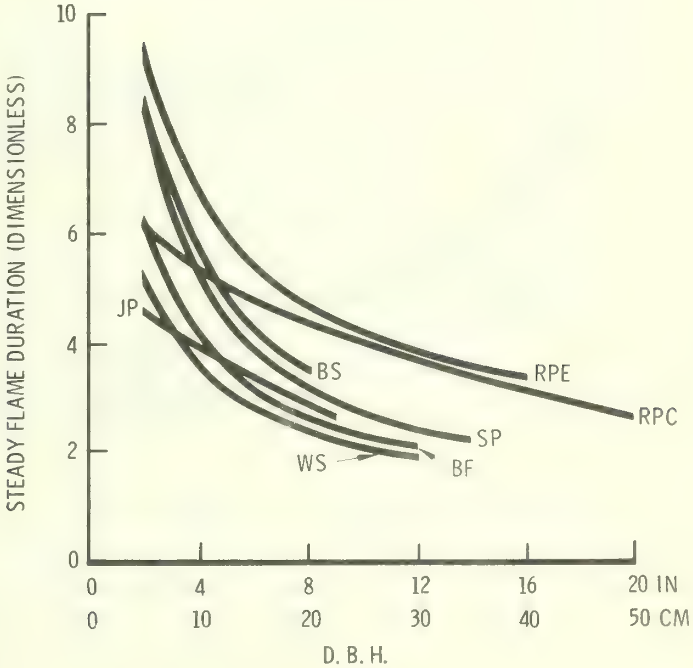


*Figure 3b.--Steady flame duration for individual tree "torching out."*



*igure 4a.--Height of "steady" flame from burning of one tree crown in still air for several species common to the North Central/Northeast U.S.A.*



*gure 4b.--Steady flame duration for individual tree "torching out."*

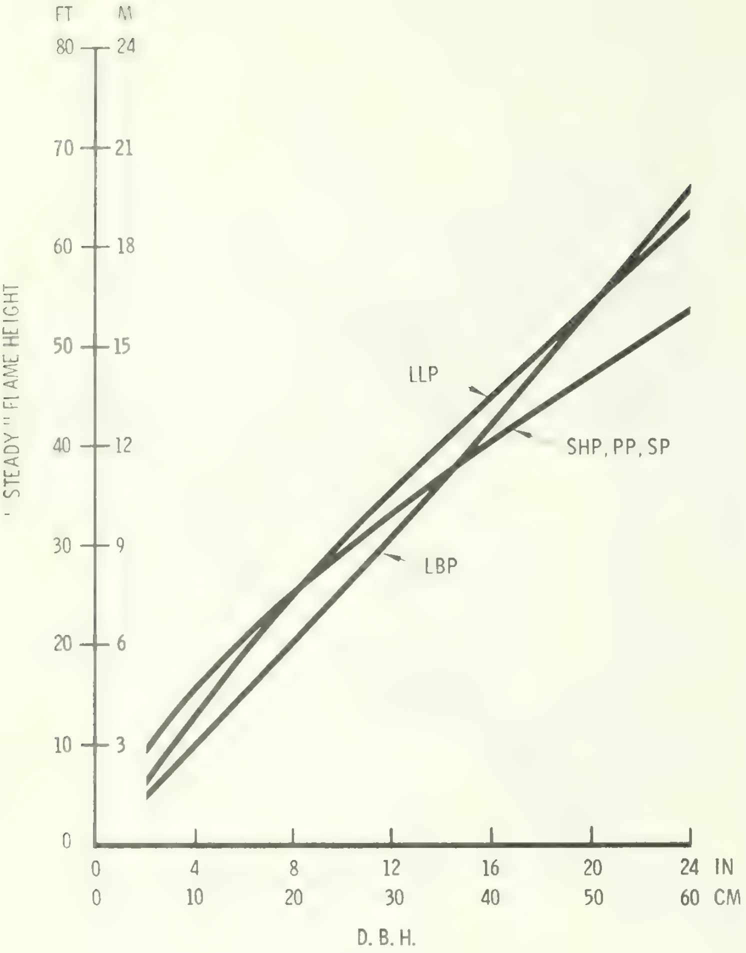


*Figure 5a.--Height of "steady" flame from burning of one tree crown in still air for several Southern/Southeastern pine speci*

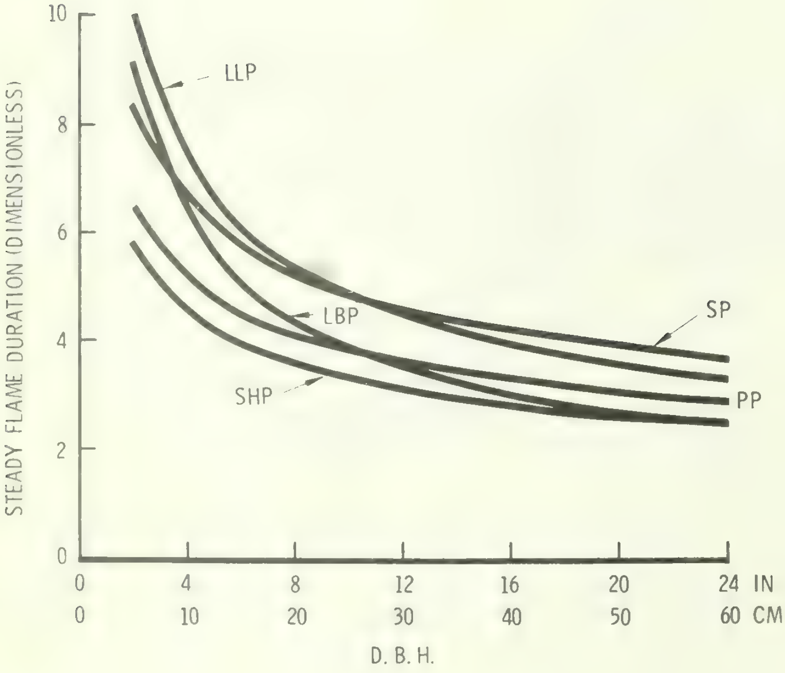


*Figure 5b.--Steady flame duration for individual tree "torching out."*

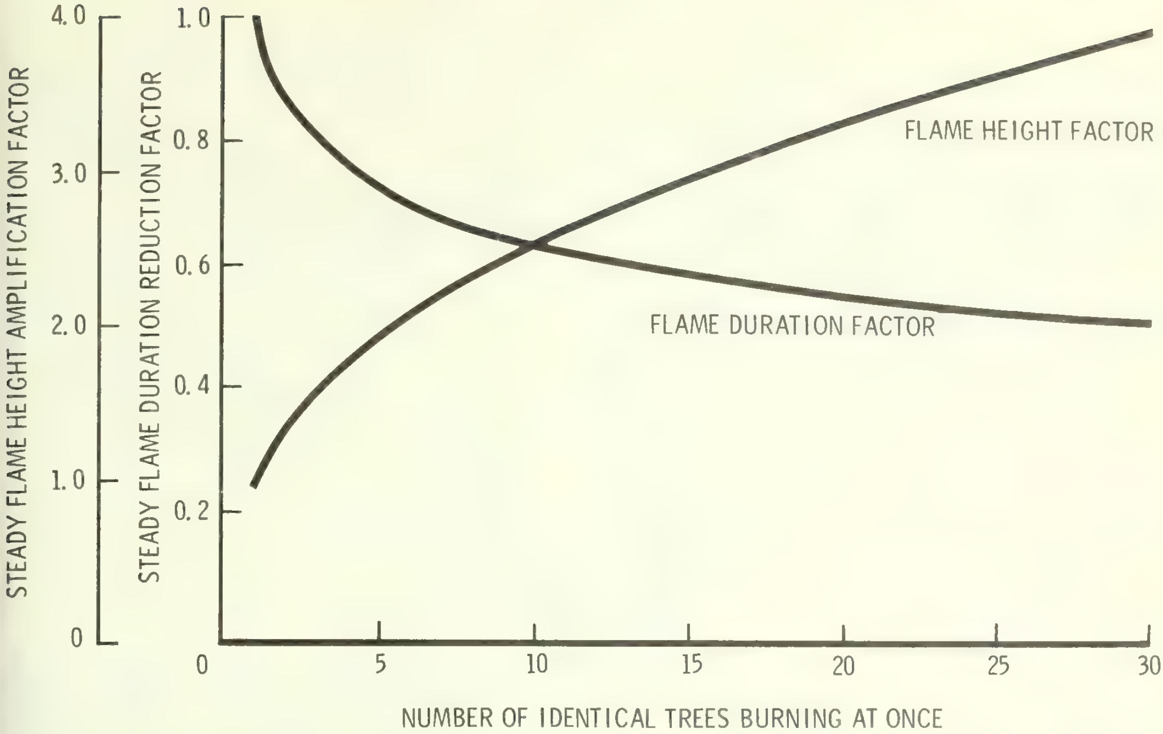


*Figure 6.--Multiplication factors for flame height and dimensionless duration to account for simultaneous burning of several identical trees that produce a single steady flame and buoyant plume structure.*

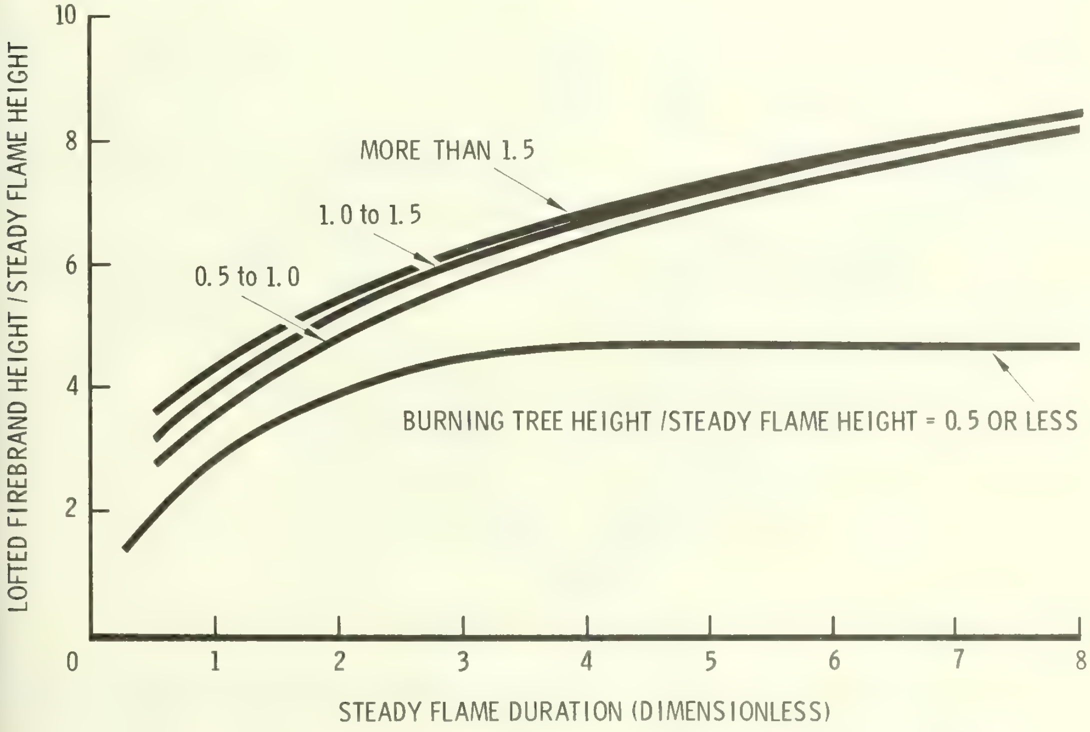


*Figure 7.--Height of firebrands lofted by burning trees.*

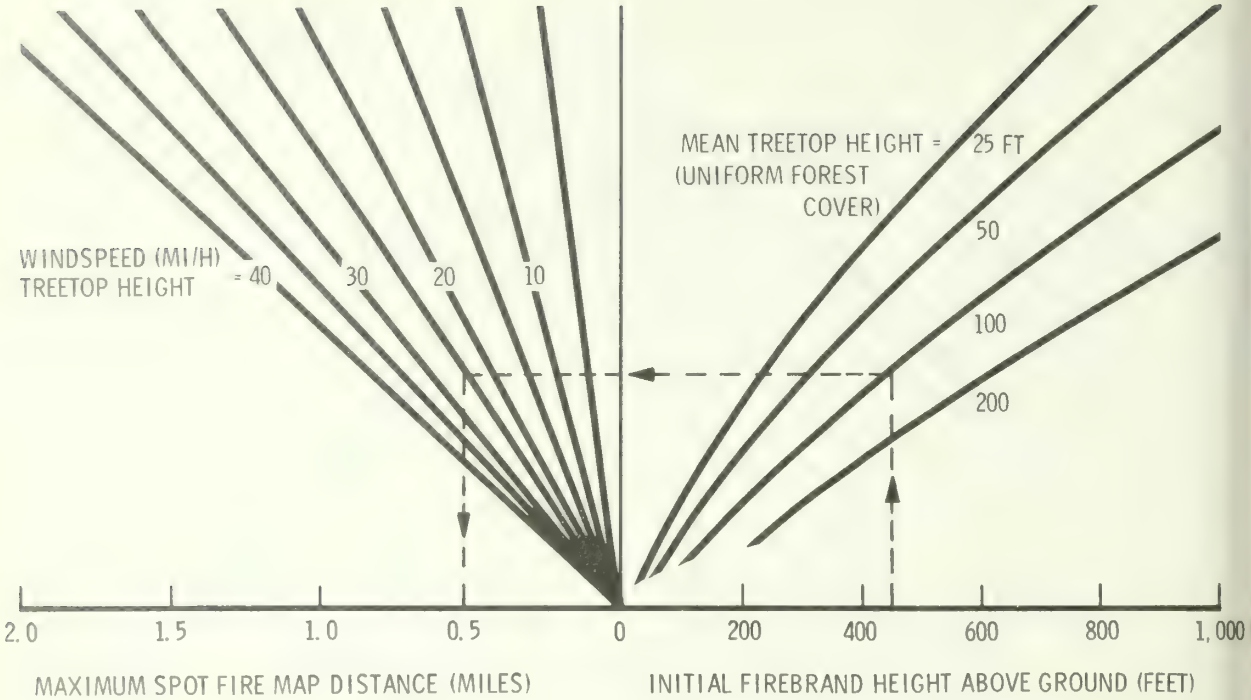


Figure 8a.--Nomograph for predicting maximum spot fire distance over flat terrain; British units of measure.

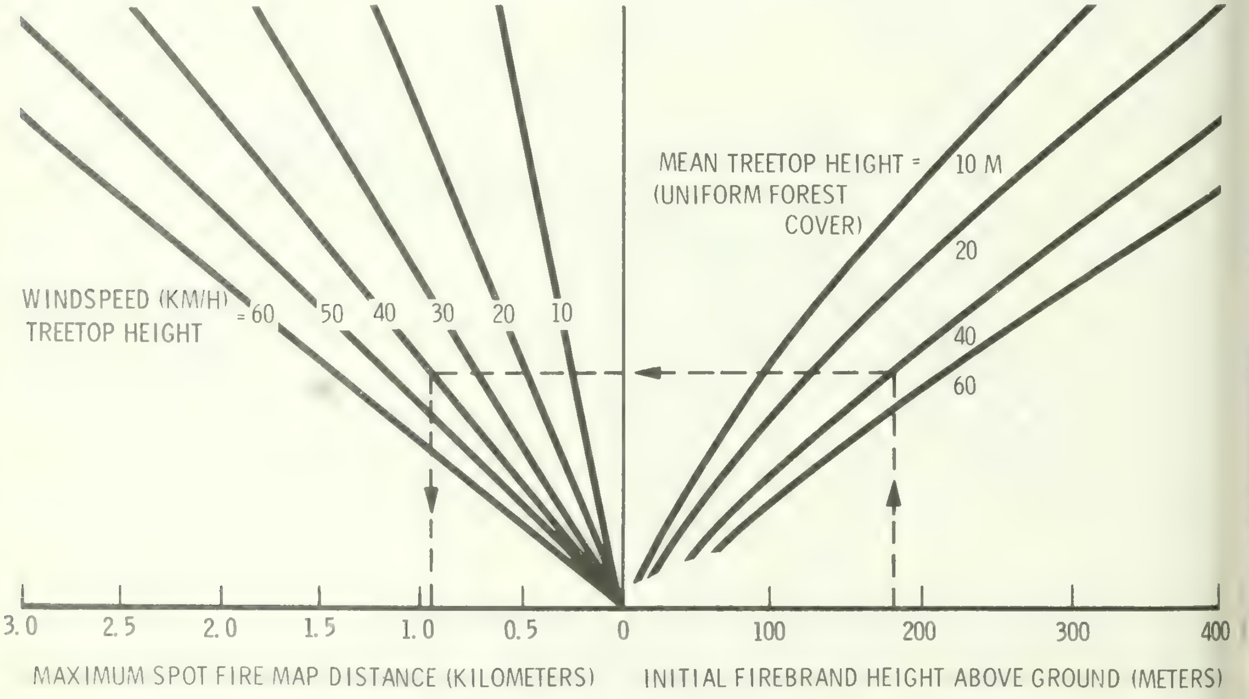


Figure 8b.--Nomograph for predicting maximum spot fire distance over flat terrain; metric units of measure.

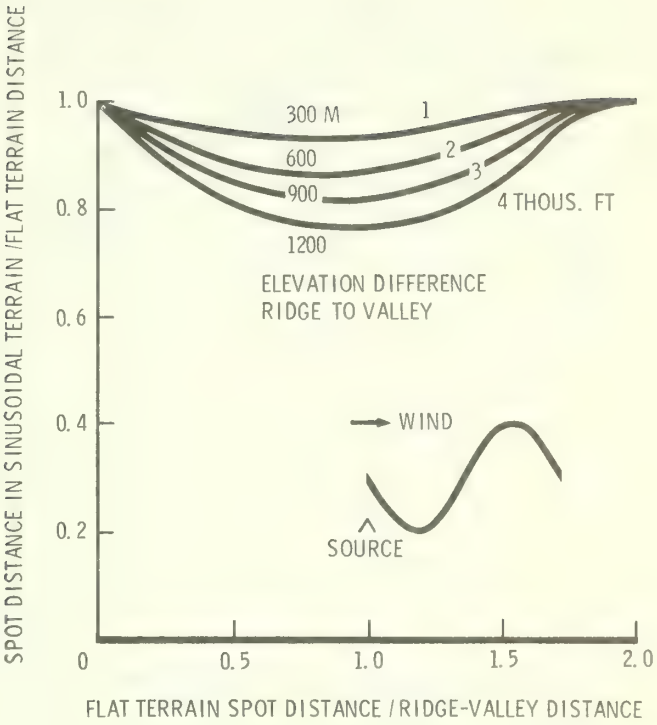
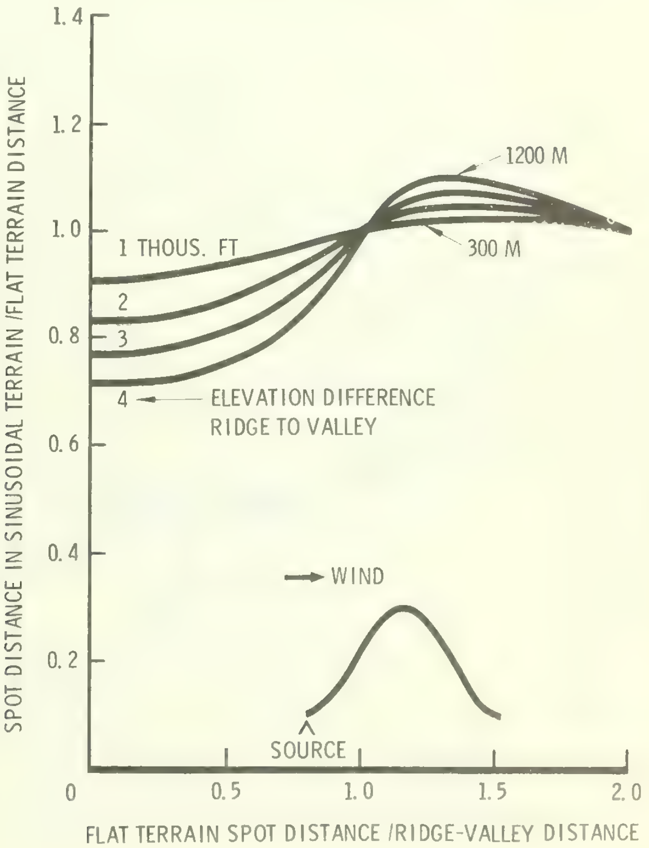


Figure 9a.--Spotting distance multiplier for sinusoidal terrain relative to flat terrain. Spot source is at midslope on leeward side. Reference wind profile is the same as the midslope profile.



igure 9b.--Spotting distance multiplier for sinusoidal terrain relative to flat terrain. Spot source is at valley bottom. Reference wind profile is the same as the midslope profile.

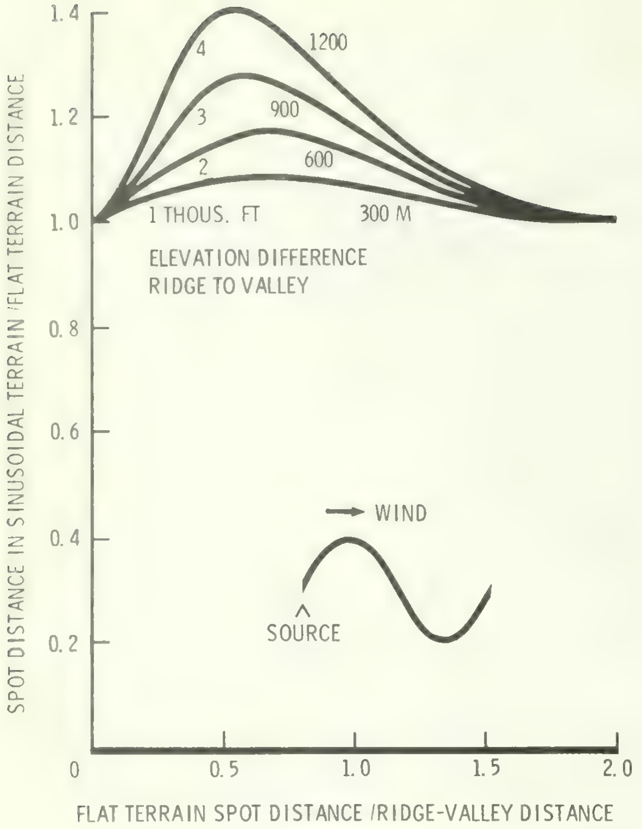


*Figure 9c.--Spotting distance multiplier for sinusoidal terrain relative to flat terrain. Spot source is at midslope on windward side. Reference wind profile is the same as the midslope profile.*

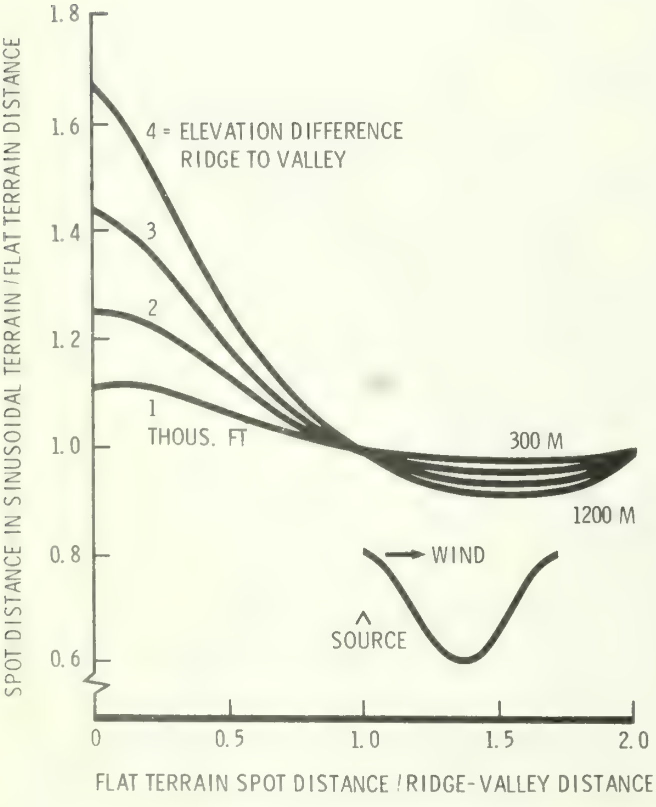


*Figure 9d.--Spotting distance multiplier for sinusoidal terrain relative to flat terrain. Spot source is at ridgetop. Reference wind profile is the same as the midslope profile.*

# EXAMPLES

Two examples are given to help familiarize the reader with computation procedures. From the statements of the problems one can obtain all the information necessary to complete the worksheets as shown. The reader is encouraged to reconstruct the process to see how each number is used.

*Example 1.* A recurrent fire control problem on the Coconino National Forest near Flagstaff, Arizona, is spotting when thickets of small Ponderosa pine torch out under strong wind. Estimate maximum spot fire distance if a group of 20 trees, each 6 inches in diameter, torches out when the windspeed is 20 mi/h, measured at the nearest Fire-Danger Rating station (i.e., a 20-foot tower anemometer in a clearing). The trees that torch out are about 50 feet tall; the terrain can be considered flat with broken cover of 50-foot trees.

This problem is shown in the completed worksheet of exhibit 2. Note that in step 5 no windspeed correction for height above terrain was necessary, since the 20-foot tower windspeed is close to the "mean treetop height" (25 feet).

WORKSHEET FOR ESTIMATING MAXIMUM SPOT FIRE DISTANCE

1. Describe trees(s) assumed to torch out.
   Species Ponderosa Pine ↑ (use in step 2) ↑ DBH 6 (cm-[✓ in]) Height 50 (m-[✓ ft]) (use in step 4)↑ Number simultaneous 20 (use in step 3, fig 6)↑
   See table II for number of figure to use in step 2.

2. The steady flame from one burning tree.
   From fig ([✓ 3A]-4A-5A): Flame height 29 (m-[✓ ft]) From fig ([✓ 3B]-4B-5B): Duration 8.2
   From fig 6: Flame height multiplier 3.25. From fig 6: Flame duration multiplier .55

3. Adjusted values: Steady flame height 94 (m-[✓ ft]). (use in step 4) ↑ Steady flame duration 4.5 (use in step 4, fig 7)↑

4. Tree height (step 1) ÷ Adjusted steady flame height (step 3) = .53 (use in fig 7)
   From fig 7: Lofted firebrand height/steady flame height 6.6.
   Multiply by adjusted steady flame height (step 3). Result: 620 (m-[✓ ft])
   Add 1/2 tree height (recorded in step 1). Result: 650 (m-[✓ ft]) (use in step 6, fig 8)

5. Windspeed adjustments. Record for reference:
   At elevation — (m-ft) at height 20 (m-[✓ ft]) windspeed is 20 (km/h-[✓ mi/h])
   Avg. elevation — (m-ft). Mean treetop height along firebrand path 25 (m-[✓ ft]) (use in fig 2 and step 6, fig 8)↑
   Difference = — (m-ft) (use in fig 2)
   From fig 2: windspeed relative to value at same height but at avg. elevation 1 (X)
   Windspeed reference height ÷ mean treetop height = 0.8 (use in fig 1 if greater than 1)
   See instructions for step 5 (use of fig 1 may not be indicated)
   From fig 1, or by estimate, windspeed at reference height relative to treetop 1 (Y)
   Divide reference windspeed by (X) and result by (Y). Result 20 (km/h-[✓ mi/h]) (use in fig 8)↑

6. From fig 8([✓ A]-B): Maximum spot distance over flat terrain .92 (km-[✓ mi])

7. Correct for terrain relief along flight path if necessary. FLAT
   Firebrand source is located nearest to:
   Leeward midslope ____ valley floor ____ windward midslope ____ ridgetop ____
   Use fig no: 9A 9B 9C 9D

   Elevation difference from ridge to valley ____ (m-ft)
   Distance from ridge to valley as would be shown on map ____ (km-mi)
   Spot distance from step 6 ÷ ridge-to-valley distance = ____ (use in fig 9)
   From fig 9(A-B-C-D): Spot distance in sinusoidal terrain/flat terrain distance ____
   Multiply by maximum spot distance over flat terrain (step 6).

   Result: .92 (km-[✓ mi])
   This is the maximum spot distance (as shown on map) estimate↑

EXHIBIT 2. EXAMPLE 1 COMPLETED

Example 2. While a wildfire is topping out on a ridge 3,000 feet above a river valley, fire scouts note that groups of 5 to 10 large Douglas-firs are torching out sporadically. These trees are near the ridgetop and flying embers may be borne across the river, about one-half mile from the ridge. The trees are probably 100 feet tall, and appear to be in the 24-30 inch d.b.h. range. The fire weather forecaster estimates the windspeed over the ridgetop to be 15-20 mi/h (presumably at treetop height). The hillside is uniformly forested with trees averaging 75 feet in height. As fire behavior officer, you are asked if you think a crew or two should be dispatched to the far side of the river to extinguish spot fires. Assuming that the humidity is low so potential spot fires can be easily ignited, what would your answer be?

This example is shown in exhibit 3. Note that the "high end" numbers are used in each case to get a maximum estimate of spot distance. So the trees are assumed to be 30 inches d.b.h., and groups of 10 are assumed to burn at one time.

WORKSHEET FOR ESTIMATING MAXIMUM SPOT FIRE DISTANCE

1. Describe tree(s) assumed to torch out.
Species Douglas-Fir DBH 30 (cm-[✓ in]) Height 100 (m-[✓ ft]) Number simultaneous 10
↑ (use in step 2) ↑ (use in step 4)↑ (use in step 3, fig 6)↑
See table II for number of figure to use in step 2.

2. The steady flame from one burning tree.
From fig ([✓ 3A]-4A-5A): Flame height 87 (m-[✓ ft]) From fig ([✓ 3B]-4B-5B): Duration 4.0

3. From fig 6: Flame height multiplier 2.5. From fig 6: Flame duration multiplier .63
Adjusted values: steady flame height 220 (m-[✓ ft]). Steady flame duration 2.5
(use in step 4) ↑ (use in step 4, fig 7)↑

4. Tree height (step 1) ÷ Adjusted steady flame height (step 3) = .45 (use in fig 7)
From fig 7: Lofted firebrand height/steady flame height 4.2.
Multiply by adjusted steady flame height (step 3). Result: 920 (m-[✓ ft])
Add 1/2 tree height (recorded in step 1). Result: 970 (m-[✓ ft]) (use in step 6, fig 8)

5. Windspeed adjustments. Record for reference:
At elevation 3000 (m-[✓ ft]) at height 75 (m-[✓ ft]) windspeed is 20 (km/h-[✓ mi/h])
Avg. elevation 1500 (m-[✓ ft]). Mean treetop height along firebrand path 75 (m-[✓ ft])
(use in fig 2 and step 6, fig 8) ↑
Difference = 1500 (m-[✓ ft]) (use in fig 2)
From fig 2: windspeed relative to value at same height but at avg. elevation 1.4 (X)
Windspeed reference height ÷ mean treetop height = 1.0 (use in fig 1 if greater than 1)
See instructions for step 5 (use of fig 1 may not be indicated)
From fig 1, or by estimate, windspeed at reference height relative to treetop 1 (Y)
Divide reference windspeed by (X) and result by (Y). Result 14 (km/h-[✓ mi/h])
(use in fig 8) ↑

6. From fig 8([✓ A]-B): Maximum spot distance over flat terrain 0.64 (km-[✓ mi])

7. Correct for terrain relief along flight path if necessary.
Firebrand source is located nearest to:
Leeward midslope ___ valley floor ___ windward midslope ___ ridgetop X
Use fig no: 9A 9B 9C [✓ 9D]
Elevation difference from ridge to valley 3000 (m-[✓ ft])
Distance from ridge to valley as would be shown on map 0.5 (km-[✓ mi])
Spot distance from step 6 ÷ ridge-to-valley distance = 1.3 (use in fig 9)
From fig 9(A-B-C-[✓ D]): Spot distance in sinusoidal terrain/flat terrain distance .95
Multiply by maximum spot distance over flat terrain (step 6).
Result: 0.61 (km-[✓ mi])
This is the maximum spot distance (as shown on map) estimate ↑

EXHIBIT 3. EXAMPLE 2 COMPLETED

# SYNOPSIS OF SUBMODEL CONTENT

The individual submodels of the prediction scheme are described in detail in the series of appendixes following. This section describes how the submodel results are fitted together and discusses some key assumptions used in developing the prediction scheme.

The steady flame structure submodel (appendix A) is a crude phenomenological description, predicting flame height to be proportional to the rate of fuel consumption raised to the power 2/5. Using this model to describe the flame from a burning tree requires that further assumptions be made. The assumptions used here are:

1. The fuel consumption rate is approximated as 70 percent of the dry weight of the crown foliage divided by a burning time fixed by the surface/volume ratio of the foliage. The factor 0.7 is an arbitrary estimate of the amount of foliage burned during the "steady" flaming period when the entire tree crown is involved in fire. The burning time formula is based on an empirical rule determined by Anderson (1969). Crown foliage weight can be predicted for many tree species from diameter at breast height (Keays 1971; Brown and others 1977).

2. The height of the base of the flame is not well defined. The steady flame model pictures the flow of combustible fuel gas through a horizontal orifice. The height of such an equivalent fuel supply plane is clearly between the ground and the top of the tree. This height represents the vertical displacement of the origin of the coordinate system in which the flame structure is described. In this presentation the origin is taken to be at half the tree height.

3. When several trees are consumed nearly simultaneously to produce a single large flame structure, the firebrand-lifting capability is increased. The flame height increase factor is taken to be $N^{2/5}$, implying merely a pooling of the combustible gases from N burning trees. Flames from neighboring fires will merge into a single structure when the flame heights are significantly greater than the distance separating them (Thomas and others 1965). By assuming that the flames always merge, we clearly follow the intention of analyzing the "worst case." The merging of the flames results in a reduction of the *dimensionless* flame duration, because the normalizing time is the time required for gas to pass through the flame structure. As the flame height, $z_F$, increases, this travel time increases as $z_F^{1/2}$. But the actual burning period stays constant, so the dimensionless measure of flame duration decreases as $N^{-1/5}$.

The buoyant plume above the steady flame is modeled (appendix B) as a self-similar, radially symmetrical, turbulent buoyant jet. The velocity and buoyancy flux are matched at the flame tip. The rest of the flow description is obtained immediately by application of well-established scaling laws. So closely related are the flame structure and plume structure models that the flame height serves to scale the plume geometry. The characteristic gas transit time also serves naturally to nondimensionalize the time history of the collapse of the plume when the fire burns out. So if the flame structure model is revised, the plume flow model will be automatically adjusted if the flame tip gas velocity scales as $z_F^{1/2}$.

The firebrand burning rate model (appendix C) used in this theory is quite similar in form to one inferred by others (Lee and Hellman 1970, Tarifa and others 1965, 1967). Numerical comparisons are difficult, however, and there is a great deal of scatter in the supporting data. This model predicts that a freely falling, burning cylinder or plate will fall at a velocity (relative to the vertical component of windspeed) that declines linearly in time. This prediction, coupled with the results from a wind field model (appendix E) that streamlines parallel the terrain, leads to a great simplification in determining the maximum possible spot fire distance.

While firebrand materials other than cylindrical stem sections are obvious candidates for analysis (Clements 1977), only minor differences in spot distance would result unless the burning rate behavior departs substantially from that used in this model. The height to which a particle will be lofted by the flame/plume flow (appendix D) depends upon the parameter group $\rho D/C_D$, where $\rho$ is the particle mean mass density, D is a linear dimension of the particle parallel to its velocity relative to the gas flow, and $C_D$ is the particle's drag coefficient. The time history of this same parameter group determines how far it will be borne by a given wind field.

Stemwood segments, needles, bark flakes, and seed-cone scales will behave quite similarly in this regard and a cylinder makes a good generic representative. Twigs with foliage attached, open whole seed cones, and clumps of moss are examples of potential firebrands that might behave differently. But even open seed cones would have substantially higher initial falling velocities than small-diameter stemwood segments (Clements 1977) so would not be carried nearly so high in the flow and could not travel as far. Moss clumps, on the other hand, could be lofted high into the air because the mean density of a highly porous clump is very low. But the "staying power" of a burning moss clump would be determined by the surface/volume ratio of the material and it usually would be consumed before returning to the ground.

A twig with foliage attached might be able to outdistance a simple wood cylinder, however. During the lofting phase of its flight it could have a low value of $\rho D/C_D$ because of a porous overall structure. But the foliage might soon be burned away, leaving a wood cylinder with a substantially higher value of $\rho D$ than the composite structure had. This would allow the particle sufficient lifetime to return to the ground before being consumed and it would start falling from a height that it could not achieve without the added drag area afforded by the foliage. Such a "two stage" firebrand presents a difficult analytical challenge--one that has not been met fully here. A cursory attempt to establish a range increase failed.

Samples of live twigs with needles attached were gathered and analyzed by the author. Four species of tree were represented in the samples: lodgepole pine, ponderosa pine, Douglas-fir, and Engelmann spruce. The needle lengths, number of needles per unit length of twig, twig diameters, needle weights, and twig weights were determined for about 10 twig segments for each species. The weight/drag ratios (or $\rho D/C_D$) of the composite structures were calculated using average values for the variables needed. Using these data in the particle height-vs-time formulas (appendix D) resulted in initial particle heights that were too great to allow the twig to return to the ground before burning out, for all the examples tried. In other words, no spot distance advantage was found for the composite firebrands. This does not mean that all combinations of twig diameter, needle length, number of needles per unit of twig length, etc., would not go farther than a stem segment. But, for the species sampled, the necessary combination was not found. No further effort was spent on "two stage" firebrand structures.

The structure of the wind field that carries the burning brand has a powerful influence on the distance it travels. For flight over forested flat terrain a simple logarithmic variation of velocity with height suffices for a windspeed model. Using the profile shown in figure 1, the path of the burning brand is readily computed. In this computation the logarithmic profile of windspeed with height is extended below treetop height to zero velocity. A maximum distance would be predicted by assuming the windspeed below treetop height to be constant. At the other extreme, one might consider the crown layer to be impenetrable by a firebrand and set the velocity to zero. Neither extreme is realistic, but the extended logarithmic profile interpolates between them, so is used for convenience.

For wind over uneven terrain--e.g., blowing across a ridge-valley system--it is necessary to model the variation of windspeed with horizontal distance (fig. 2) and to include the vertical wind component as well. The crude model developed in appendix E includes these variations, but omits some well established features of such a wind field:

1. The variation of windspeed and direction with height commonly called the Ekman spiral (see, e.g., Brown 1974) is not included in the model. An isobar at constant height is used in the model as a "lid" on the flow beneath it, as done by Fosberg and others (1976) and friction is ignored down to a thin layer close to the surface. In this surface friction layer the logarithmic profile used in the flat terrain model is employed, with a characteristic horizontal velocity that depends on local terrain height.

2. The "rotor" or recirculation flow often observed on the lee side of a ridge (Schroeder and Buck 1970) is not included in the wind model. There exist mathematical models of windflow over terrain features that include "rotor" and "lee wave" effects (Alaka 1960) but they are complex and demand more data than just the terrain profile. Trial use of the simplified wind model presented here will reveal whether or not the simplification has degraded its accuracy beyond utility in rough terrain.

3. The friction length scale of the flow in the friction layer is treated as a constant in this model. Its value is set to 0.1313 times the average treetop height, based upon measured data in relatively flat terrain with a uniform forest cover (Tanner and Pelton 1960; Marunich 1975). This may prove to be a weak point in the velocity profile model because uniform forest cover over nonuniform terrain with significant elevation change is not the usual case. The user is asked to select an "average" canopy top height when assessing maximum spotting distance, but no guidance is given for determining the appropriate average when forest cover and open areas must both be considered.

Determination of the trajectory of the firebrand particle carried by the model flow fields is straightforward. Although some approximations are made in the analyses, each can be justified quantitatively. It is felt that the approximations and model uncertainties in the burning rate and wind field descriptions dominate errors introduced in calculating the flight of the particle. The lofting phase of the trajectory (appendix E) is treated less precisely than the transport phase (appendix F) but in neither case should the integration of the equations of motion introduce error as large as the uncertainties in the models on which they are based.

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# APPENDIX A: FLAME STRUCTURE MODEL

In this appendix a simple phenomenological model is presented for the structure of a large flame burning in still air. Approximate expressions are developed for the mean length (height) of the flame, the velocity of the gas flow within the flame, and the dynamic pressure profile. To derive these expressions a model of such a flame is postulated and analyzed. Although the model is obviously oversimplified and incorrect in detail, the gross relationships sought do not justify a more elaborate model. And the transparency of the model allows one to see the influence of various parameters (and assumptions) on the quantities sought.

## I. *Conceptual Model*

Picture an erect right circular cone as a boundary in space. This cone marks the region within which exists gaseous fuel.[4] The fuel flows into the region axially across the circular area at the base and is consumed at the surface of the cone as it makes contact with the air. The tip of the cone is the tip of the flame. The cone of fuel gas is surrounded by a cylindrical sheath of varying radius within which flow the products of combustion plus entrained ambient air. In this annular sheath the gas flows upward, as does the fuel gas. Outside this sheath, ambient air flows radially inward toward the vertical axis of the flame. The following symbols will be used to describe the flows and boundaries discussed:

*Symbols*

$\rho$ = gas density (mass/unit volume)
$r$ = radial distance from central axis
$z$ = vertical distance from base of flame
$u$ = inward radial velocity
$w$ = upward axial velocity
$\phi$ = mean mass ratio of air to fuel producing flame-product/air mix
$\eta$ = entrainment velocity ratio ($u/w$), a constant with height by assumption
$g$ = acceleration of gravity

*Subscripts*

| | |
|---|---|
| f | refers to fuel gas (condition or boundary location) |
| a | refers to ambient air (condition or boundary location) |
| p | refers to products of reaction (plus admixed air) |
| o | refers to conditions at the base of the flame |
| F | refers to conditions at the tip of the flame |

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[4] The gaseous fuel consists of the products of volatilization and pyrolysis of the solid fuel being burned, plus some combustion products and some poorly mixed air. In this simplified model the mixture is idealized as pure gaseous fuel.

## II. Mathematical Model

Using these symbols we can write the conservation equations of the gross flame structure. The entrainment assumption (Thomas 1963; Thomas and others 1965; Turner 1973) is made here in the form:

$$u = \gamma w \qquad \text{(A1)}$$

and w is assumed to be a function of z only. The conservation of mass and momentum are readily expressed in terms of an intermediate variable, m, representing the mass in a unit height of the entire flame structure, divided by π:

$$m = \rho_p\left(r_a^2 - r_f^2\right) + \rho_f r_f^2. \qquad \text{(A2)}$$

The conservation of mass relationship is then:

$$\frac{d}{dz}(mw) = 2\rho_a r_a u. \qquad \text{(A3)}$$

The air/fuel ratio involved in forming the "product" gas (not chemical stoichiometry) is specified by the parameter ϕ. Holding ϕ constant leads to:

$$mw + \phi\rho_f w r_f^2 = (1 + \phi)(\rho_f w r_f^2)_o. \qquad \text{(A4)}$$

The conservation of momentum, including the effects of buoyancy and "drag" due to air entrainment is expressed by:

$$mw\frac{dw}{dz} = g(r_a^2\rho_a - m) - 2\rho_a r_a uw. \qquad \text{(A5)}$$

These equations are essentially the same as those used by others (Steward 1964; Morton 1965; Nielsen and Tao 1965) in models of flame size.

Using equations (A2) and (A4) one can derive the following useful intermediate relationship:

$$wr_a^2 = \left\{\frac{\rho_f}{\rho_p}\left(\frac{1 + \phi}{\phi}\right) - \frac{1}{\phi}\right\}\frac{mw}{\rho_f} - \left(\frac{1 + \phi}{\phi}\right)\left(\frac{\rho_f}{\rho_p} - 1\right)(wr_f^2)_o. \qquad \text{(A6)}$$

Here it has also been assumed that the inner core of fuel is at constant density:

$$\rho_f = (\rho_f)_o. \qquad \text{(A7)}$$

Using equation (A6) in equation (A5) multiplied through by w gives:

$$mw^2\frac{dw}{dz} = \rho_a g\left\{\frac{mw}{\rho_f}\left(\frac{\rho_f}{\rho_p}\left(\frac{1 + \phi}{\phi}\right) - \frac{1}{\phi}\right) - \left(\frac{1 + \phi}{\phi}\right)\left(\frac{\rho_f}{\rho_p} - 1\right)(wr_f^2)_o\right\} - mwg - 2\rho_a r_a uw^2. \qquad \text{(A8)}$$

In a shorthand form this can be written as

$$w\frac{d}{dz}(mw^2) = g(\alpha mw - \beta(mw)_o) \qquad \text{(A9)}$$

where α and β are constants given by:

$$\alpha = \left(\frac{1 + \phi}{\phi}\right)\frac{\rho_a}{\rho_p} - \frac{1}{\phi}\frac{\rho_a}{\rho_f} - 1 \tag{A10}$$

$$\beta = \left(\frac{1 + \phi}{\phi}\right)\frac{\rho_a}{\rho_f}\left(\frac{\rho_f}{\rho_p} - 1\right). \tag{A11}$$

Note that the mass conservation and entrainment equations combined can be written as:

$$\begin{aligned} \frac{d}{dz}(mw) &= 2\eta\rho_a r_a w = 2\eta\rho_a w^{1/2}(w r_a{}^2)^{1/2} \\ &= 2\eta\rho_a w^{1/2}\left\{\frac{\alpha + 1}{\rho_a}mw - \frac{\beta}{\rho_a}(mw)_o\right\}^{1/2} \\ &= 2\eta\left\{\rho_a w\left((\alpha + 1)mw - \beta(mw)_o\right)\right\}^{1/2} \end{aligned} \tag{A12}$$

or

$$m^{1/2}\frac{d}{dz}(mw) = 2\eta\left\{(mw)\rho_a\left((\alpha + 1)mw - \beta(mw)_o\right)\right\}^{1/2}. \tag{A13}$$

Multiplying (A9) through by (mw) makes the left hand side a perfect differential:

$$\frac{d}{dz}\left((mw^2)^2\right) = 2gmw\left(\alpha mw - \beta(mw)_o\right). \tag{A14}$$

Equations (A13) and (A14) are now further simplified by noting that, over most of the length of the flame,

$$\alpha mw >> \beta(mw)_o, \tag{A15}$$

an inequality that arises from the large ratio of air to fuel noted for natural fires (Thomas 1963). By eliminating the second term from the righthand side of (A13) and (A14) one arrives at[5]

$$m^{1/2}\frac{d}{dz}(mw) \doteq 2\eta\left((\alpha + 1)\rho_a\right)^{1/2} mw \tag{A16}$$

$$\frac{d}{dz}\left((mw^2)^2\right) \doteq 2\alpha g(mw)^2. \tag{A17}$$

Substituting the expressions:

$$P = mw; \quad Q = mw^2 \tag{A18}$$

into these equations gives:

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[5] Actually, it is not necessary to make this approximation to proceed with the analysis, but the difference resulting is minor and therefore not justifiable in view of the level of accuracy of this model.

$$(P/Q^{1/2})\frac{dP}{dz} = 2\eta\big((\alpha + 1)\rho_a\big)^{1/2}P \qquad (A19)$$

$$\frac{dQ^2}{dz} = 2\alpha g P^2 \qquad (A20)$$

or

$$\frac{dP}{dz} = 2\eta\big((\alpha + 1)\rho_a\big)^{1/2}Q^{1/2} \qquad (A21)$$

$$\frac{dQ}{dz} = \alpha g P^2/Q. \qquad (A22)$$

Dividing one equation by the other gives:

$$\frac{dP}{dQ} = \frac{2\eta}{\alpha g}\big((\alpha + 1)\rho_a\big)^{1/2}Q^{3/2}/P^2 \qquad (A23)$$

or

$$\frac{2}{5}\,Q^{5/2} - \frac{\alpha g}{2\eta}\,\frac{\frac{1}{3}\,P^3}{\big((\alpha + 1)\rho_a\big)^{1/2}} = \text{constant} = \frac{2}{5}\,S \qquad (A24)$$

$$Q^{1/2} = \left\{S + \frac{5}{12}\,\frac{\alpha g P^3}{\eta\big((\alpha + 1)\rho_a\big)^{1/2}}\right\}^{1/5}. \qquad (A25)$$

## III. *Flame Length*

This last expression can be used directly in equation (A21) to provide a formula for flame length. Note that

$$\frac{dP}{dz} = 2\eta\big((\alpha + 1)\rho_a\big)^{1/2}\left\{S + \frac{5}{12}\,\frac{\alpha g}{\eta\big((\alpha + 1)\rho_a\big)^{1/2}}\,P^3\right\}^{1/5}. \qquad (A26)$$

Evaluating the constant S at the base of the flame gives:

$$S = (mw^2)_o^{5/2} - \frac{5\alpha g}{12\eta}\,\frac{(mw)_o^{\,3}}{\big((\alpha + 1)\rho_a\big)^{1/2}} \qquad (A27)$$

so that (A26) can be written in terms of P normalized by its value at the flame base, $P_o$, in the form

$$\frac{d(P/P_o)}{\left\{1 + \frac{5}{12}\,\frac{\alpha g}{\eta\big((\alpha + 1)\rho_a\big)^{1/2}}\,\frac{m_o^{1/2}}{w_o^{2}}\left(\left(\frac{P}{P_o}\right)^3 - 1\right)\right\}^{1/5}} = \frac{2\eta\big((\alpha + 1)\rho_a\big)^{1/2}}{m_o^{1/2}}\;dz. \qquad (A28)$$

ow, since

$$(P/P_o)\big|_{z=z_F} = P_F/P_o = 1 + \phi, \tag{A29}$$

he flame length formula is:

$$2\eta\left(\frac{\rho_a(\alpha + 1)}{m_o}\right)^{1/2} z_F = \int_1^{1+\phi}\left\{1 + \frac{5}{12}\,\frac{\alpha g}{\eta\left((\alpha + 1)\rho_a\right)^{1/2}}\,\frac{m_o^{1/2}}{w_o^{2}}(x^3 - 1)\right\}^{-1/5} dx. \tag{A30}$$

The second term in the radical in the integrand is much larger than unity over ost of the length of the flame so that, to a level of approximation consistent with his analysis we have:

$$2\eta\left(\frac{\rho_a(\alpha + 1)}{m_o}\right)^{1/2} z_F \doteq \left\{\frac{12}{5}\,\frac{\eta\left(\rho_a(\alpha + 1)\right)^{1/2} w_o^{2}}{\alpha g m_o^{1/2}}\right\}^{1/5} \int_1^{1+\phi} x^{-3/5}dx$$

$$\doteq \left\{\frac{12}{5}\,\frac{\eta\left(\rho_a(\alpha + 1)\right)^{1/2} w_o^{2}}{\alpha g m_o^{1/2}}\right\}^{1/5} \frac{5}{2}\left((1 + \phi)^{2/5} - 1\right). \tag{A31}$$

his result is very similar to that obtained by Steward (1964) and exhibits the ower law found by other investigators (Wohl and others 1949; Putnam and Speich 63; Putnam 1965).

Thomas (1963) presents experimental data in dimensionless form, with which this rmula can be compared. In the notation used here, his dimensionless form can be itten as

$$z_F/2(r_a)_o = K\left\{(\rho_f w)_o/\left(\rho_a(2r_{a,o}g)^{1/2}\right)\right\}^N \tag{A32}$$

here K and N are empirical constants. Noting that

$$m_o = (\rho_f r_f^{2})_o = (\rho_f r_a^{2})_o, \tag{A33}$$

quation (A31) can be cast in the form of (A32), with the result:

$$N = \frac{2}{5} \tag{A34}$$

$$K = \frac{5}{2}\left(\frac{24}{5}\right)^{1/5}\left(\frac{\eta}{\alpha}\right)^{1/5}\frac{(1 + \phi)^{2/5} - 1}{4\eta(\alpha + 1)^{2/5}}. \tag{A35}$$

e numerical value of K for natural fires is to be estimated by using appropriate lues for $\phi$, $\eta$, and the density ratios appearing in the parameter $\alpha$. Typical lues might be (Thomas 1963)

$$\rho_a/\rho_p = 8/3; \quad \rho_a/\rho_f = 5/3; \quad \phi = 30; \quad \eta = 0.075. \tag{A36}$$

Using these values we find

$$K = 12.4 \tag{A37}$$

which value is about half of that reported by Thomas (1963) for the experiments of Putnam and Speich (1963) using city gas, adjusted for the ratio of heat content of wood volatiles to that of methane. The exponent (N) of 2/5 is the dimensionally correct value and is a good correlation value for the data of Putnam and Speich, although Thomas reports better agreement with a variety of wood crib data using an exponent of 0.61. Note that if one replaces the lower limit of the integral in equation (A31) with zero--amounting to complete neglect of the fuel gas flow at the base of the flame with respect to the flow of product gas at the tip --the equation for the flame length becomes

$$z_F/2(r_a)_o = 16\left\{(\rho_f w)_o/\rho_a(2gr_{a,o})^{1/2}\right\}^{2/5} \tag{A38}$$

using the constants given in (A36) above. This expression gives a better fit than K = 12.4 to the experimental data given in Thomas' survey, and will be used in this paper.

## IV. *Gas Velocity and Dynamic Pressure*

The mean gas velocity within the flame can be expressed in terms of the distance from the flame base, using the expressions developed above. From (A25) and (A27) we can write $(w/w_o)$ in terms of $(P/P_o)$, since Q is wP:

$$w/w_o = Q/w_oP = \left\{(mw^2)_o^{5/2} + \frac{5}{12}\frac{\alpha g}{\eta}\frac{(mw)_o^3}{\left(\rho_a(\alpha+1)\right)^{1/2}}\left(\left(\frac{P}{P_o}\right)^3 - 1\right)\right\}^{2/5} \Big/ (w_oP). \tag{A39}$$

Again neglecting the smaller terms in the radical this can be approximated by:

$$w \doteq \left\{\frac{5}{12}\frac{\alpha g}{\eta}\frac{P_o^{1/2}}{\left((\alpha+1)\rho_a\right)^{1/2}}\right\}^{2/5}\left(\frac{P}{P_o}\right)^{1/5}. \tag{A40}$$

The dependence of $(P/P_o)$ on z is readily obtained from (A31) by replacing $z_F$ by z and $(1+\phi)$ by $(P/P_o)$. So doing leads to the form:

$$w \doteq \left\{\frac{5}{12}\frac{\alpha g}{\eta}\frac{P_o^{1/2}}{\left((\alpha+1)\rho_a\right)^{1/2}}\right\}^{2/5}\left\{1 + \frac{4\eta}{5}\left(\frac{\rho_a(\alpha+1)}{m_o}\right)^{1/2}\left(\frac{5}{12}\frac{\alpha g}{\eta w_o^2}\left(\frac{m_o}{\rho_a(\alpha+1)}\right)^{1/2}\right)^{1/5} z\right\}^{1/2}. \tag{A41}$$

This expression simplifies also, since we are concerned only with the upper part of the flame, where the second term in the radical on the righthand side is much greater than unity. Neglecting the one leads to considerable cancellation of factors:

$$w \doteq (\alpha gz/3)^{1/2}. \tag{A42}$$

The value of $\alpha$, from (A10), is very nearly

$$\alpha \doteq \rho_a/\rho_P - 1 \tag{A43}$$

since $\phi$ is about 30. This leads to the form:

$$w \doteq 0.408\left(2g(\rho_a/\rho_P - 1)z\right)^{1/2}. \tag{A44}$$

The only difference between this expression and the empirical equation given in Thomas (1963), based on experimental work by Rasbash and others (1956) with liquid fuel fires, is the numerical factor. Thomas reports a coefficient of 0.36, or 12 percent less than the value here. The difference is no doubt due to the gross nature of this model.

The mean density within the flame structure is needed to describe the dynamic pressure profile. Average density ($\bar{\rho}$) is readily derivable from the variables already used; since by definition of average

$$\bar{\rho} = m/r_a^2 = mw/(wr_a^2) = P/(wr_a^2). \tag{A45}$$

From (A2), (A6), (A7), and (A10) we have

$$wr_a^2 = \frac{\alpha + 1}{\rho_a} P - \beta \frac{P_o}{\rho_a} \tag{A46}$$

so that

$$\bar{\rho}/\rho_a = P\left((\alpha + 1)P - \beta P_o\right)^{-1} = \left((\alpha + 1) - \beta P_o/P\right)^{-1}. \tag{A47}$$

This expression simplifies by referring the mean density to the value at the tip of the flame and using the scaling law for the parameter P referred to its value at the flame tip:

$$P/P_F \doteq (z/z_F)^{5/2}; \quad P \doteq (1 + \phi)P_o(z/z_F)^{5/2}. \tag{A48}$$

Using this form and noting that $\bar{\rho}$ at the flame tip is $\rho_P$, equation (A47) can be approximated for the upper part of the flame by:

$$\bar{\rho}/\rho_P \doteq \left(1 + (1 - \rho_P/\rho_f)(1 - (z_F/z)^{5/2})/\phi\right)^{-1}. \tag{A49}$$

From this form it is apparent that, over most of the upper part of the flame, the density can be considered constant and equal to the flame tip value.

The dynamic pressure, referred to its value at the tip of the flame is quickly derived now:

$$\bar{\rho}w^2/\rho_P w_F^2 = \frac{\bar{\rho}}{\rho_P}\left(\frac{w}{w_F}\right)^2 = \left(\frac{z}{z_F}\right)\Big/\left(1 - \frac{(1 - \rho_P/\rho_f)}{\phi}\left(\left(\frac{z_F}{z}\right)^{5/2} - 1\right)\right). \tag{A50}$$

### V. *Formulae Used in Firebrand Lofting Analysis*

The formulae derived above can be cast in practical form for use in the firebrand lofting computations. Equation (A38) gives the flame height, but in terms difficult to apply. It can be simplified if one observes that the rate of fuel consumption (mass per unit time, $\dot{M}$) can be written as:

$$\dot{M} = \pi\rho_f(r_a^2 w)_o . \tag{A51}$$

Inserting this into (A38) and canceling out $(r_a)_o$ gives

$$z_F \doteq 16(4/\pi\rho_a g^{1/2})^{2/5}(\dot{M})^{2/5} . \tag{A52}$$

Assuming approximately standard atmospheric conditions

$$\rho_a = 0.075 \text{ lb/ft}^3 = 1.2 \text{ kg/m}^3 \tag{A53}$$

$$g = 32 \text{ ft/s}^2 = 9.8 \text{ m/s}^2 \tag{A54}$$

so

$$z_F = 25(\dot{M})^{2/5} \tag{A55}$$

where the flame height is in feet and the fuel consumption rate is in pounds mass per second, or

$$z_F = 10.4(\dot{M})^{2/5} \tag{A56}$$

if the units are meters and kilograms per second. Figure A-1 compares predicted flame heights, using this equation, to values observed in the burning of wood cribs. The data were transcribed graphically from figures presented by Thomas (1963). The agreement between the predicted heights and observed heights is quite satisfactory, but application of the equation to burning trees involves extrapolation beyond the range shown in figure A-1.

For velocity all one needs to do is express the value at height z as a function of the flame tip value

$$w/w_F = (z/z_F)^{1/2} \tag{A57}$$

and calculate $w_F$ from (A44). Here we assume that the density ratio $\rho_a/\rho_p$ is 8/3, as before,[6] to obtain

---

[6] In other words, the flame edge is defined as the 500 C outline, about the limit of carbon particle visibility, and the product gas molecular weight is essentially that of air.

$$w_F = \begin{cases} 4.2 z_F^{1/2} & \text{ft/s}, \quad z_F \text{ in ft} \\ 2.3 z_F^{1/2} & \text{m/s}, \quad z_F \text{ in m.} \end{cases} \tag{A58}$$

The peak dynamic pressure in the flame occurs at the flame tip in this model, and the value would be given by $q_F$, where

$$q_F = \frac{1}{2} \rho_p w_F^2 = \frac{1}{6} \rho_a g z_F (1 - \rho_p/\rho_a) \tag{A59}$$

or

$$q_F = \begin{cases} 0.0078\ z_F & \text{lbf/ft}^2, \quad z_F \text{ in ft} \\ 1.23\ z_F & \text{N/m}^2, \quad z_F \text{ in m.} \end{cases} \tag{A60}$$

For all practical purposes the dynamic pressure can be considered to increase linearly with height.

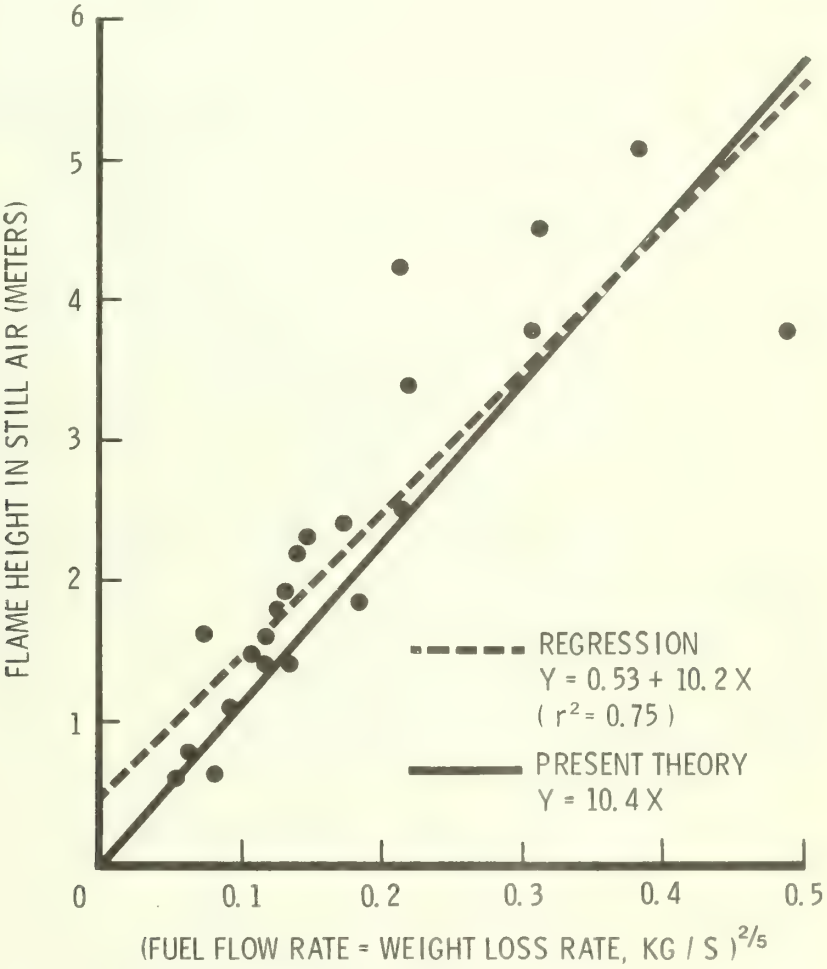

*Figure A-1.--Comparison of data on flame heights (Laboratory Wood Crib Burns, Thomas 1963) with predictions from present theory.*

# APPENDIX B: THE BUOYANT PLUME ABOVE A STEADY FLAME

The vertical transport of a firebrand into the prevailing windstream may include a period of flight in the buoyant plume flow above the flame from which it came. This "lofting" phase can be approximated by an upper-limit calculation, as discussed in the text. To perform the trajectory calculations it is necessary to describe the fluid flow field in the buoyant plume. From the tip of the (transient) flame upward we use here the scaling laws for a fully-developed turbulent buoyant plume in still air.

The decay of velocity in a buoyant plume occurs through accretion of ambient air into the flow. In still air this process is usually represented by an "entrainment parameter" as used in appendix A, giving the ratio of inflow velocity to vertical velocity. The entrainment parameter is of the order of 0.1, so use of a "still air" model clearly gives an upper limit to the firebrand-lofting capability of the plume. A plume in a shearing wind environment would be eroded more rapidly with height.

The fact that the plume is treated as fully developed (that is, steady rather than changing with time) is probably not as conservative as it may seem. This is so because prior to the "torching" of the tree or trees that produce the plume, a substantial fire must have burned in the same place for a considerable period of time. This fire will have established a convection plume that is then merely amplified by the heat pulse from the burning tree crown(s).

Well-accepted analysis of a free buoyant plume (Turner 1973) provides the scaling laws needed. The simplest applicable model is one that describes the self-similar flow field for constant buoyant flux. Let

$b$ = mean radius of plume
$G$ = buoyancy = $g(1 - \bar{\rho}/\rho_a)$
$\bar{w}$ = mean vertical velocity
$F$ = buoyant flux = $\bar{w}b^2G$ = constant

here

$g$ = acceleration of gravity
$\bar{\rho}$ = mean density in the plume
$\rho_a$ = ambient air density.

he scaling laws of interest are (Turner 1973)

$$b = \frac{6}{5}\eta z \tag{B1}$$

$$\bar{w} = \frac{5}{6\eta}\left(\frac{9}{10}\eta F\right)^{1/3} z^{-1/3} \tag{B2}$$

$$G = \frac{5F}{6\eta}\left(\frac{9}{10}\eta F\right)^{-1/3} z^{-5/3} \tag{B3}$$

here $z$ is height and $\eta$ is the entrainment parameter.

Forming ratios of these variables with their values at the tip of the flame (where $z = z_F$) we have:

$$\bar{w}/w_F = (z_F/z)^{1/3} \tag{B4}$$

$$G/G_F = (1 - \bar{\rho}/\rho_a)/(1 - \rho_P/\rho_a) = (z_F/z)^{5/3}. \tag{B5}$$

The mass density at the tip of the flame is $\rho_P$, as in appendix A. The density profile is given by

$$\bar{\rho}/\rho_a = 1 - (1 - \rho_P/\rho_a)(G/G_F) = 1 - (1 - \rho_P/\rho_a)(z_F/z)^{5/3} \tag{B6}$$

which leads directly to the dynamic pressure decay law:

$$q/q_F = (\bar{\rho}/\rho_P)(\bar{w}/w_F)^2 \tag{B7}$$

$$q/q_F = \left(1 - (1 - \rho_P/\rho_a)(z_F/z)^{5/3}\right)(\rho_a/\rho_P)(z_F/Z)^{2/3}. \tag{B8}$$

Using the nominal density ratio

$$\rho_P/\rho_a = 3/8 \tag{B9}$$

that was used in appendix A, equation (B8) becomes

$$q/q_F = (8/3)\left(1 - (5/8)(z_F/z)^{5/3}\right)(z_F/z)^{2/3}. \tag{B10}$$

Equation (B10) exhibits a maximum, due to the fact that the density increase rate exceeds the velocity decrease rate in the lower part of the plume. This feature assures that a firebrand particle lifted within the flame should be projected above the height of maximum dynamic pressure, which is at about 1.6 times flame height. The region between the flame tip and somewhere near this height can be thought of as a transition zone between the flame and the dissipating plume above it.

In order to express analytically the flight of a particle borne in the flame/plume flow structure it is necessary to approximate the power-law relationships given above by simpler forms. The "transition zone" concept is valuable in formulating the needed approximations. As noted in appendix A, the mean fluid density is nearly constant in the upper half of the flame, while the velocity increases as the square root of height. In the transition zone the density increases substantially while the velocity changes very little. Above the transition zone, the density again rises slowly while the velocity gradually decays. Simplified approximations, based on fitting the curve forms given in this and the previous appendix, are listed below:

$$\bar{\rho}/\rho_a = \begin{cases} 3/8 & , \ z \le z_F \\ (3/8)(z/z_F), & z_F < z < 1.4\ z_F \\ 0.525 & , \ z \ge 1.4\ z_F \end{cases} \qquad \text{(B11)}$$

$$\bar{w}/w_F = \begin{cases} (z/z_F)^{1/2} & , \ z \le z_F \\ 1 & , \ z_F < z < 1.4\ z_F \\ (5.963/(4.563 + z/z_F))^{1/2}, & z \ge 1.4\ z_F. \end{cases} \qquad \text{(B12)}$$

These simpler forms are used in the analysis of trajectories of potential firebrands. The density is underestimated by the approximate form and the velocity is overestimated, but the dynamic pressure is accurately described (fig. B-1). Overestimation of the velocity is consistent with the intent here to estimate an upper bound for spotting distance; the misestimation takes the form of a shift upward (of about 2 flame heights) of the velocity-vs-height curve.

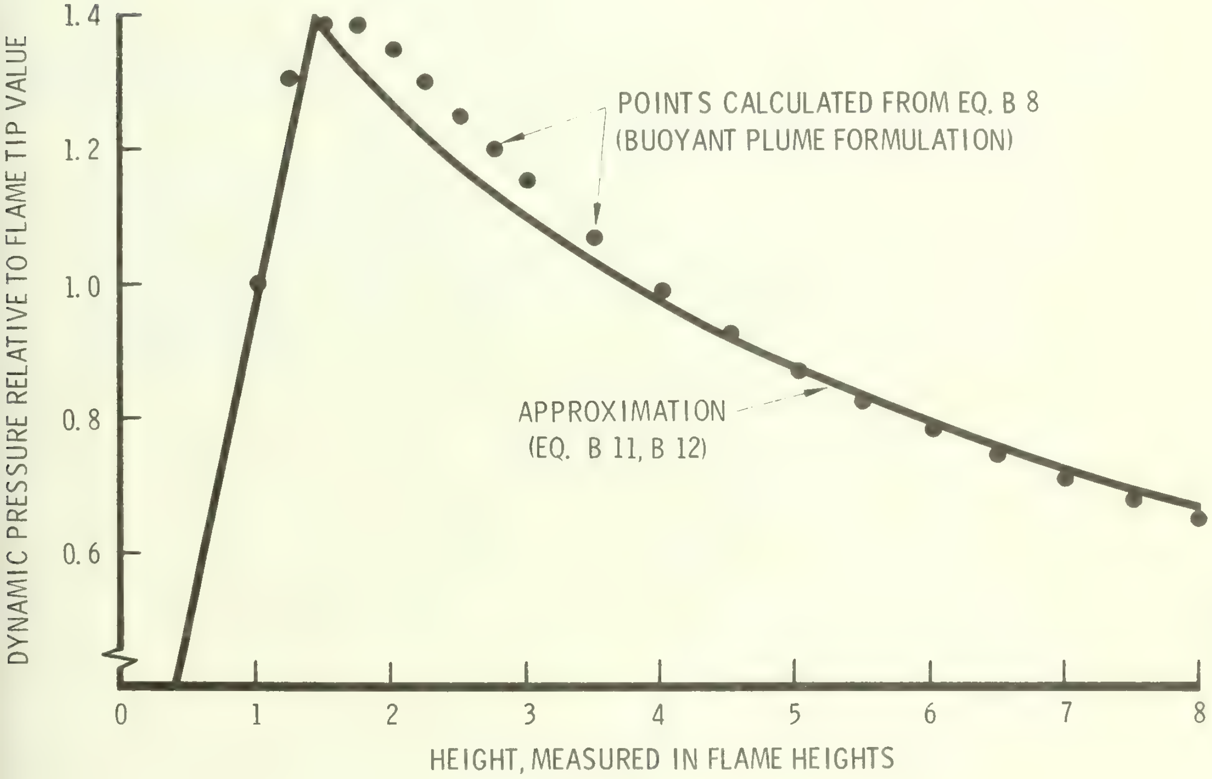

*Figure B-1.--Dynamic pressure profile in and above steady flame, showing approximation used in calculating firebrand lifting ability.*

# APPENDIX C: FIREBRAND BURNING RATE MODEL

A firebrand burning in flight changes aerodynamic properties in at least two ways simultaneously. It loses mass and it loses volume. Woody material is pyrolyzed by heat supplied by combustion on the outer surface of the piece, and is eventually reduced totally to char. The density of char is less than that of sound or partially decayed wood, so a firebrand also loses density. By losing both density and volume, the firebrand reduces its terminal fall velocity, since that velocity is proportional to the square root of the product of density and linear dimension in the direction of relative wind (Tarifa and others 1965).

We are dealing with relatively small, light objects as firebrands here so terminal fall velocity is achieved in a short distance. The subsequent flight of the object is dictated by the changes in terminal velocity over time (or distance). Thus the simplest model one might construct to represent the burning of firebrands in flight would be one that allowed the prediction of terminal fall velocity directly. This fact was recognized by Tarifa and others (1967). The final product of that investigation was a correlation of terminal velocity with a complicated variable that is linear in time. The correlation curve is roughly bell-shaped.

The data reported in these earlier investigations dealt with various object shapes (plates, cylinders, and spheres) of differing sizes and made from different woods. These objects do not necessarily typify naturally occurring potential firebrands, but the fact that they all yielded a similar behavior pattern encourages the use of a "universal" burning rate law.

Data taken at the Northern Forest Fire Laboratory[7] on limbwood sections with bark cover were used to develop the model used in this analysis. The burning rate law is postulated from dimensional considerations and can be derived as follows. Let

$M$ = mass of burning particle
$\rho_s$ = mean density of particle
$D$ = dimension of particle in direction of relative wind
(= thickness of plate, diameter of cylinder or sphere)
$A$ = cross-sectional area presented to wind by particle
$U$ = velocity of wind over particle
$\rho_a$ = density of air.

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[7] Data reported by Muraszew and others (1975).

The rate of mass loss is supposed to be proportional to the rate of supply of air to the surface (Lee and Hellman 1970);

$$\frac{dM}{dt} = -K_1 \rho_a AU \tag{C1}$$

where $K_1$ is a dimensionless constant. Since

$$M = C \rho_s AD \tag{C2}$$

where C is a geometrical constant fixed by the shape of the particle, equation (C1) can be written as

$$A \frac{d}{dt}(\rho_s D) + \rho_s D \frac{dA}{dt} = - \frac{K_1}{C} \rho_a AU. \tag{C3}$$

The data on limbwood sections (table C-1) showed the fractional decrease in A usually to be much less than the fractional decrease in M over most of the lifetime of burning brands,[8] so to a fair approximation one might neglect the second term on the left-hand side of (C3) and obtain

$$\frac{d}{dt}(\rho_s D) \doteq \frac{K_1}{C} \rho_a U = -K\rho_a U. \tag{C4}$$

For constant windspeed, such as in the wind tunnel tests, equation (C4) can be integrated to give:

$$(\rho_s D)/(\rho_s D)_o = 1 - K\rho_a Ut/(\rho_s D)_o \tag{C5}$$

where the subscript o indicates the initial value of the parameter. This is the form that was used to estimate a value for the constant K. A constrained linear regression of the form

$$y = bx \tag{C6}$$

with

$$y = 1 - (\rho_s D)/(\rho_s D)_o \tag{C7}$$

$$x = \rho_a Ut/(\rho_s D)_o \tag{C8}$$

was performed on the data from 33 tests on ovendried limbwood sections. The variable y was established by using

$$y = 1 - \left((\rho_s M)/(\rho_s M)_o\right)^{1/2} \tag{C9}$$

since both mass and density were determined after fixed periods of burning, but diameter was not directly measured except for a limited series of samples.

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[8] For cylinders in cross flow, A is the product of length and diameter (D). While D changed, the length was essentially constant unless the piece fractured.

Table C-1.--*Firebrand burning rate data. Data are for ovendry limbwood samples, each initially 5 inches long*

| pecies f tree | Nominal diam. | Initial values Mass | Initial values Density | Final values Mass | Final values Density | Derived values† $D/D_o$ | Derived values† $\rho D/(\rho D)_o$ | Wind-speed | Test time |
|---|---|---|---|---|---|---|---|---|---|
| | inches | g | g/cc | g | g/cc | | | mi/h | s |
| PP* | 1 | 53.36 | 0.610 | 4.16 | 0.240 | 0.445 | 0.175 | 15 | 360 |
| PP | 1 | 47.20 | .520 | 6.47 | .260 | .523 | .262 | 15 | 300 |
| PP | 1 | 44.59 | .584 | 5.32 | .220 | .562 | .212 | 15 | 240 |
| PP | 1 | 31.33 | .472 | 9.42 | .239 | .771 | .390 | 15 | 180 |
| PP | 1 | 41.33 | .559 | 13.31 | .467 | .621 | .519 | 15 | 120 |
| ES | 1 | 48.44 | .706 | 6.99 | .329 | .557 | .259 | 15 | 360 |
| ES | 1 | 50.70 | .755 | 9.69 | .340 | .652 | .293 | 15 | 300 |
| ES | 1 | 45.41 | .577 | 18.46 | .307 | .874 | .465 | 15 | 240 |
| ES | 1 | 73.05 | .779 | 28.39 | .461 | .810 | .480 | 15 | 180 |
| ES | 1 | 74.60 | .777 | 42.01 | .600 | .854 | .659 | 15 | 120 |
| WL | 1 | 29.59 | .564 | 2.74 | .132 | .629 | .147 | 15 | 240 |
| WL | 1 | 21.15 | .474 | 3.01 | .128 | .726 | .196 | 15 | 180 |
| WL | 1 | 23.00 | .475 | 7.08 | .230 | .796 | .387 | 15 | 120 |
| WRC | 1 | 51.14 | .583 | 1.76 | .099 | .449 | .077 | 15 | 300 |
| WRC | 1 | 42.41 | .511 | 3.00 | .118 | .553 | .128 | 15 | 240 |
| WRC | 1 | 46.25 | .543 | 9.70 | .277 | .641 | .327 | 15 | 180 |
| WRC | 1 | 40.38 | .550 | 13.28 | .300 | .777 | .423 | 15 | 120 |
| PP | 0.5 | 11.54 | .536 | 0.76 | .053 | .815 | .081 | 10 | 180 |
| PP | .5 | 14.01 | .660 | 2.85 | .143 | .968 | .210 | 10 | 150 |
| PP | .5 | 10.76 | .547 | 2.13 | .106 | .010 | .196 | 10 | 120 |
| PP | .5 | 7.74 | .347 | 2.33 | .127 | .907 | .260 | 10 | 90 |
| ES | .5 | 22.46 | .786 | 2.16 | .106 | .844 | .114 | 10 | 180 |
| ES | .5 | 23.98 | .746 | 3.86 | .153 | .886 | .182 | 10 | 150 |
| ES | .5 | 20.33 | .696 | 2.60 | .099 | .949 | .135 | 10 | 120 |
| S | .5 | 36.83 | .750 | 16.85 | .484 | .842 | .543 | 10 | 90 |
| WL | .5 | 18.45 | .468 | 1.71 | .102 | .652 | .142 | 10 | 180 |
| WL | .5 | 21.75 | .699 | 5.16 | .263 | .794 | .299 | 10 | 150 |
| WL | .5 | 22.81 | .623 | 5.26 | .231 | .789 | .293 | 10 | 120 |
| L | .5 | 16.61 | .485 | 9.01 | .314 | .915 | .592 | 10 | 90 |
| RC | .5 | 20.25 | .529 | 1.45 | .077 | .700 | .102 | 10 | 180 |
| RC | .5 | 19.04 | .529 | 2.51 | .123 | .752 | .175 | 10 | 150 |
| RC | .5 | 18.93 | .522 | 3.34 | .214 | .656 | .269 | 10 | 120 |
| RC | .5 | 17.09 | .585 | 3.09 | .191 | .745 | .243 | 10 | 90 |

PP = Ponderosa pine; ES = Engelmann spruce; WL = Western larch; WRC = Western ed cedar.

$D/D_o$ = diameter ratio inferred from square root of mass ratio ÷ density ratio; $D/(\rho D)_o$ = density ratio times diameter ratio.

Substantial scatter was evident in the data, and two sources of such scatter can be identified. In some trials not all of the sample burned. When only part of the length of the section burned, the final density and mass would be much greater than in those cases where the whole section burned. Also, in some trials (especially for longer burn times) the sample would burn through and pieces would be blown away. In these cases the final mass (but not final density) would be significantly lower than in cases that had whole samples at the end of the run. The records showing which tests suffered which defect (if any) were not available[9] at the time of this analysis, so all data were used, with the foreknowledge that the results would include significant variation. Figure C-1 illustrates the scatter mentioned.

Although not enough data are available yet to quantify the process, the burning of wood pieces under forced convection appears to proceed in three stages. In the first stage, the dimensions of the piece appear to change insignificantly, if at all, but the mass drops as the outer portions pyrolyze. In the final stage, the piece remaining is entirely reduced to char and mass loss proceeds from shrinkage of the size of the piece as it burns away by glowing combustion. Between these two stages a transition phase exists during which a char layer is being formed and being eroded simultaneously. Comprehensive models of this process have been attempted by several workers (see, e.g., Kanury 1974; Kung 1971) but they are so complicated that the level of refinement of the rest of this analysis precludes their use here. The simplistic model employed here should suffice for order-of-magnitude computation.

As shown on the graph of figure C-1, the regression coefficient value obtained was

$$b = K = 0.0064. \qquad \text{(C10)}$$

This number was used in deriving the maximum range formulas graphed in the text. Revision of this number by including more experimental data can easily be reflected in the results, as is shown in appendix F.

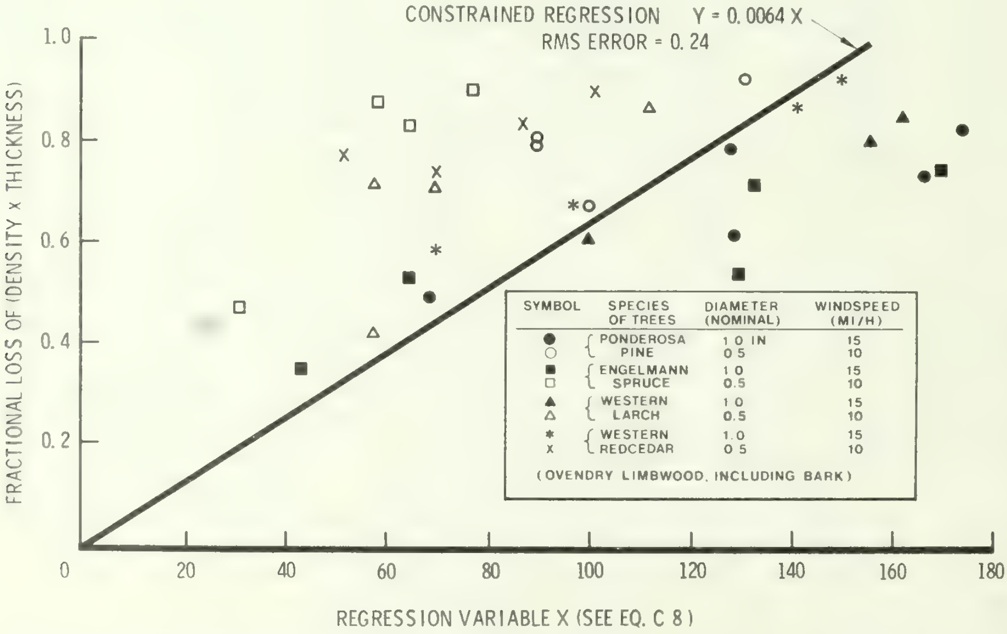

*Figure C-1.--Data used to establish firebrand burning rate model.*

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[9] Records had been discarded for lack of storage space.

# APPENDIX D: LOFTING OF FIREBRANDS BY FLAME AND BUOYANT PLUME

In this appendix a model is developed for the process by which potential fire- rands are lofted into the buoyant plume above a steady flame. The flame is, of urse, from a burning tree or group of trees, so is not truly steady, but transient. he flame/buoyant plume structure is treated as a steady flow field but is permitted o collapse, from the bottom upward, when the foliage of the burning tree(s) is onsumed. The potential firebrand is represented in this model as an insert cylin- er with specific gravity typical of weathered wood.

The analysis proceeds in three phases. First an approximate formula is deve- oped for the velocity of a firebrand in the vertical flow field. This formula is hen applied to derive the height of the particle as a function of time, assuming hat the flow field is truly steady. The demise of the flow field is then approxi- ted by using the steady state gas velocity versus height equations to predict the ogress of the last bit of flame product upward through the flow structure. With e passage of this imaginary surface, the flow is presumed to be terminated as a herent structure, leaving any particles "overtaken" to be transported by the wind eld from the height at which they are when overtaken.

## 1 *Velocity of an Inert Particle in a Constant Vertical Flow Field*

The lifting of a potential firebrand by the flow field within and above a rning tree can be described approximately by considering an idealization of the ocess. The particle starts presumably from rest and is accelerated by aerody- mic drag upward against the pull of gravity. As will be shown below, particles at have terminal fall velocities not greatly different from the fluid velocity e accelerated rapidly (in a short distance as well as in a short time) to the eed at which the force of gravity is just balanced by the drag induced by its locity relative to the gas. This fact leads to the useful approximation that e particle is borne by the (variable) flow field at such a speed as to produce e drag/gravity balance everywhere. So the first step in the model development to describe the acceleration of an inert particle from rest by a constant flow eld. The following variables are used in this description:

$m$ = mass of inert particle
$v$ = vertical velocity of particle
$t$ = time
$\rho$ = gas density
$C_D$ = drag coefficient of particle
$A$ = area presented to flow by particle
$w$ = gas velocity (vertical)
$g$ = acceleration of gravity.

The equation of motion can be written as

$$m \frac{dv}{dt} = \frac{1}{2} \rho C_D A (w - v)^2 - mg \qquad \text{(D1)}$$

ad put in dimensionless form by defining the following variables:

$$v_o = \text{terminal fall velocity in still fluid} = (2mg/\rho C_D A)^{1/2} \tag{D2}$$

$$\theta = gt/v_o \tag{D3}$$

$$s^* = (w - v)/v_o = \text{normalized "slip velocity"} \tag{D4}$$

$$\frac{ds^*}{d\theta} = 1 - (s^*)^2. \tag{D5}$$

The slip velocity history given by integrating (D5) is

$$s^* = 1 + 2/\left(\left(\frac{w + v_o}{w - v_o}\right) \exp(2\theta) - 1\right) \tag{D6}$$

when the particle starts from rest at time $t = 0$. This equation shows that the ultimate slip velocity, $v_o$, is approached closely within a very brief period of time. For example, if $v_o$ is 10 ft/sec, then in one second $\theta$ has a value of 3.2 and, even if $w$ is very much greater than $v_o$, the slip velocity has fallen to within 0.3 percent of its "final" value. The distance covered in that time may be large, however, so (D6) must be integrated again to define the spatial history of the particle velocity. Denoting particle height by $z$, note that:

$$\frac{dz}{dt} = v = w - v_o s^*. \tag{D7}$$

In terms of dimensionless variables

$$z^* = gz/v_o^2 \tag{D8}$$

$$w^* = w/v_o \tag{D9}$$

and using (D6) for $s^*$ we have

$$\frac{dz^*}{d\theta} = w^* - 1 - \frac{2(w^* - 1)\exp(-2\theta)}{(w^* + 1) - (w^* - 1)\exp(-2\theta)}. \tag{D10}$$

The last term in (D10) is a perfect differential, so

$$z^* = (w^* - 1)\theta - \ln\big((w^* + 1 - (w^* - 1)\exp(-2\theta))/2\big) \tag{D11}$$

if $z$ is zero at time $t = 0$. Recasting (D6) in terms of the ratio of particle velocity to ultimate particle velocity,

$$v^* = v/(w - v_o) \tag{D12}$$

we can write the velocity and height equations as:

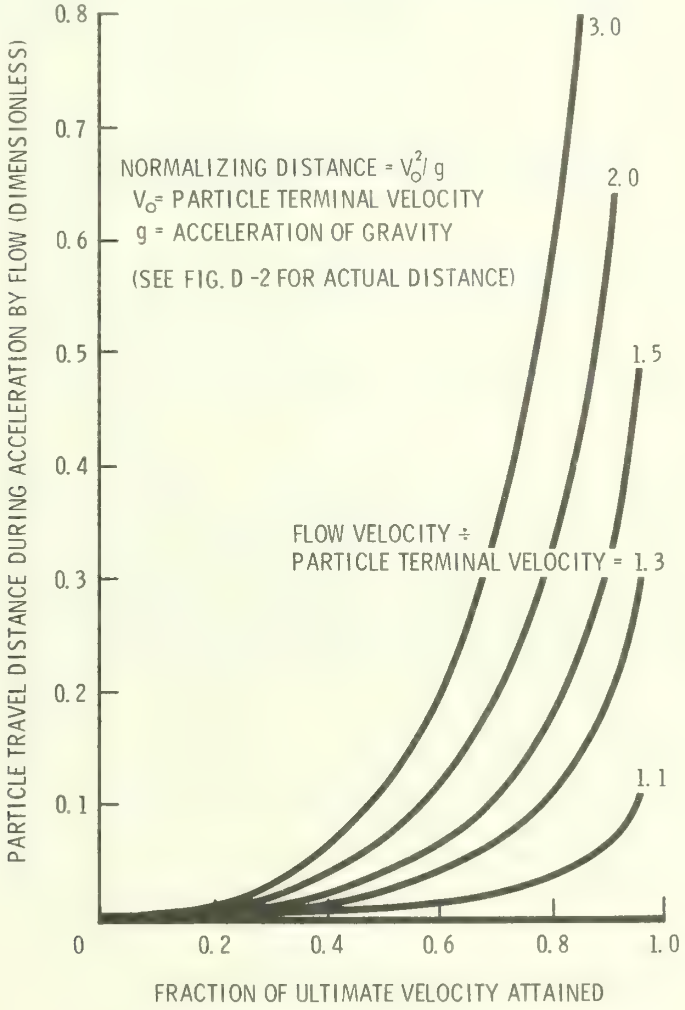
$$v^* = 1 - 2/((w^* + 1)\exp(2\theta) - (w^* - 1)) \tag{D13}$$

$$z^* = (w^* + 1)\theta + \ln(1 - v^*). \tag{D14}$$

These equations are graphed in figure D-1 as a crossplot of z* as a function of v*. For typical firebrand particles we are interested in "terminal velocity" values, $v_o$, of about 10 feet per second (Clements 1977). Figure D-2 shows actual vertical distances traveled by particles accelerated from rest in constant flow by the time they have achieved 90 percent of their ultimate velocities. This figure shows that particles of the type considered good candidates for firebrands achieve a "steady" slip velocity that balances the force of gravity in a very short distance in the flow conditions typical of the flames from burning trees (see appendixes A, B). Thus the approximation is made:

*The particle everywhere travels at the velocity which balances drag and particle weight.*

This approximation will overestimate the firebrand-lofting capability of any given flow structure, but not by a substantial amount. For particles traveling in spatially variable flows, this approximation greatly simplifies the analysis. The variable flow field of the flame/plume structure is addressed below.



*igure D-1.--Distance traveled by particle accelerated upward from rest by constant-velocity flow.*

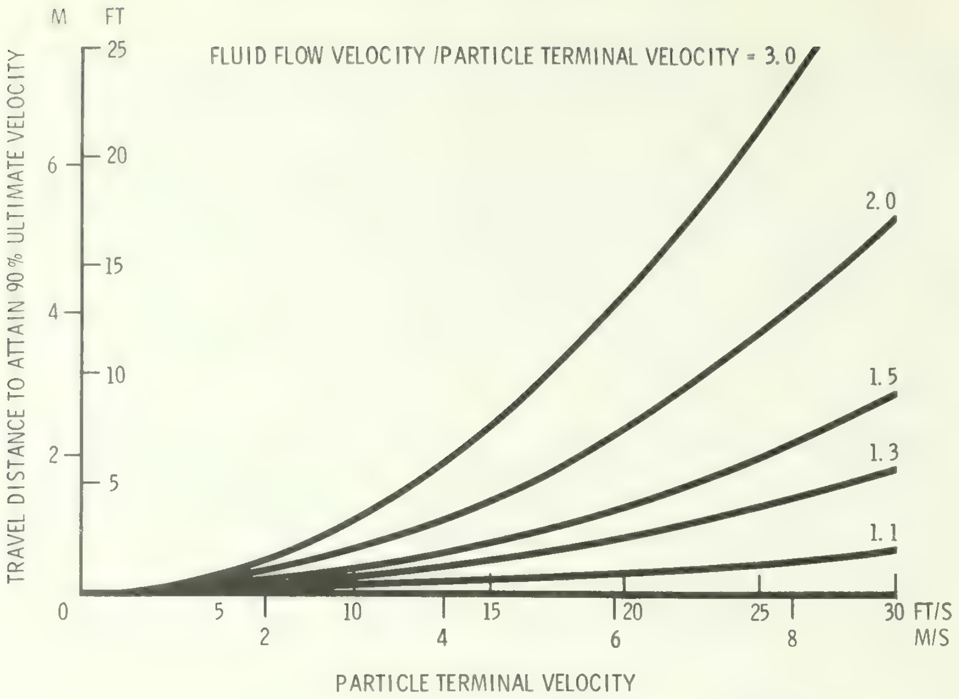


*Figure D-2.--Distance required for particle to accelerate upward to 90 percent of ultimate velocity, starting from rest, in constant fluid flow.*

## II. *Particle Trajectories in Flame/Plume Flow Fields*

The motion of an inert particle entrained in the flow through the upper part of a steady flame is approximated here by the equation

$$\frac{dz}{dt} = w - v_o \tag{D15}$$

where the fluid velocity, w, is a function of height, z, but $v_o$ is assumed to be constant. This implies that the density of the flame gas is constant. The variation of the density is minor (appendix A, eq. A49) and influences $v_o$ only as the square root of density, so use of the flame-tip value is justified here. The variation of w with z is adequately described by the approximation

$$w = w_F(z/z_F)^{1/2} \tag{D16}$$

where the subscript F denotes flame tip value.

Equation (D15) is readily integrated to yield the time, $t_F$, required for the particle to travel from its initial height, $z_o$, to the flame tip:

$$\frac{w_F t_F}{2z_F} = 1 - (z_o/z_F)^{1/2} + \frac{v_o}{w_F} \ln\left\{\frac{1 - v_o/w_F}{(z_o/z_F)^{1/2} - v_o/w_F}\right\}. \tag{D17}$$

By using the expression for $w_F$ developed in appendix A and by expressing $v_o$ in terms of the diameter of a cylinder the pertinent times and physical sizes can be made more apparent:

$$v_o/w_F = B(D/z_F)^{1/2} \tag{D18}$$

where

$$B = \left(\frac{3\pi}{2C_D}\left(\frac{\rho_s}{\rho_a}\right)\Big/\left(1 - \rho_p/\rho_a\right)\right)^{1/2} \tag{D19}$$

and

$$\left.\begin{aligned} C_D &= \text{drag coefficient} = 1.2 \text{ for cylinder in cross flow}^{10} \\ \rho_s &= \text{density of cylinder} \\ \rho_a &= \text{density of ambient air} \\ \rho_p &= \text{density of flame gases at flame tip.} \end{aligned}\right\} \tag{D20}$$

The parameter group, $2z_F/w_F$, which divides the time in equation (D17) is the time required for fluid to travel from the base to the tip of the flame. This time is a characteristic scale time for the flow and is used frequently in this analysis to normalize travel time.

Using representative values for the densities in expression (D19)

$$\rho_s = 0.3 \text{ gm/cc} \quad (19 \text{ lb/ft}^3) \tag{D21}$$

$$\rho_a = 1.2 \times 10^{-3} \text{ gm/cc} \quad (0.075 \text{ lb/ft}^3) \tag{D22}$$

$$\rho_p/\rho_a = 3/8. \tag{D23}$$

The value of B is found to be about 40. This value was used to construct figure D-3. This figure shows the travel time from initial height ($z_o$) to flame tip as a function of $D/z_F$. The time becomes indefinitely large when the fluid velocity at the initial height approaches the terminal velocity of the cylinder in the flame gas. But for those cylinders that start at half the flame height or greater, the travel time is generally less than 1.5 unless the diameter is nearly equal to the value that will not permit the particle to be lifted by the flow.

In the "transition zone" between the tip of the flame and the buoyant plume, the particle's terminal velocity decreases because the fluid density increases, but the fluid flow velocity is essentially constant:

$$\frac{dz}{dt} = w_F - v_{ot} \tag{D24}$$

---

[10] Most objects, unless aerodynamically shaped for stable flight, will tend to assume the orientation that maximizes drag when in unconstrained flight. The drag coefficient for cylinders (or flat disks) to be used here is about 1.2.

where

$$v_{ot} = v_o(z_F/z)^{1/2} \tag{D25}$$

and $v_o$ is the particle's terminal velocity in fluid with a density equal to that at the flame tip. The travel time, $t_t$, through the transition zone (from $z = z_F$ to $z$ = $1.4z_F$) is given by the integral of (D24). Expressed in dimensionless form as before this time is:

$$\frac{w_F t_t}{2z_F} = \frac{1}{2}\int_{z_F}^{1.4z_F}\left\{1 + \frac{v_o/w_F}{\left(\frac{z}{z_F}\right)^{1/2} - \frac{v_o}{w_F}}\right\}\frac{dz}{z_F} \tag{D26}$$

$$= 0.2 + \frac{v_o}{w_F} + \left(\frac{v_o}{w_F}\right)^2 \ln\left\{\frac{(1.4)^2 - v_o/w_F}{1 - v_o/w_F}\right\}. \tag{D27}$$

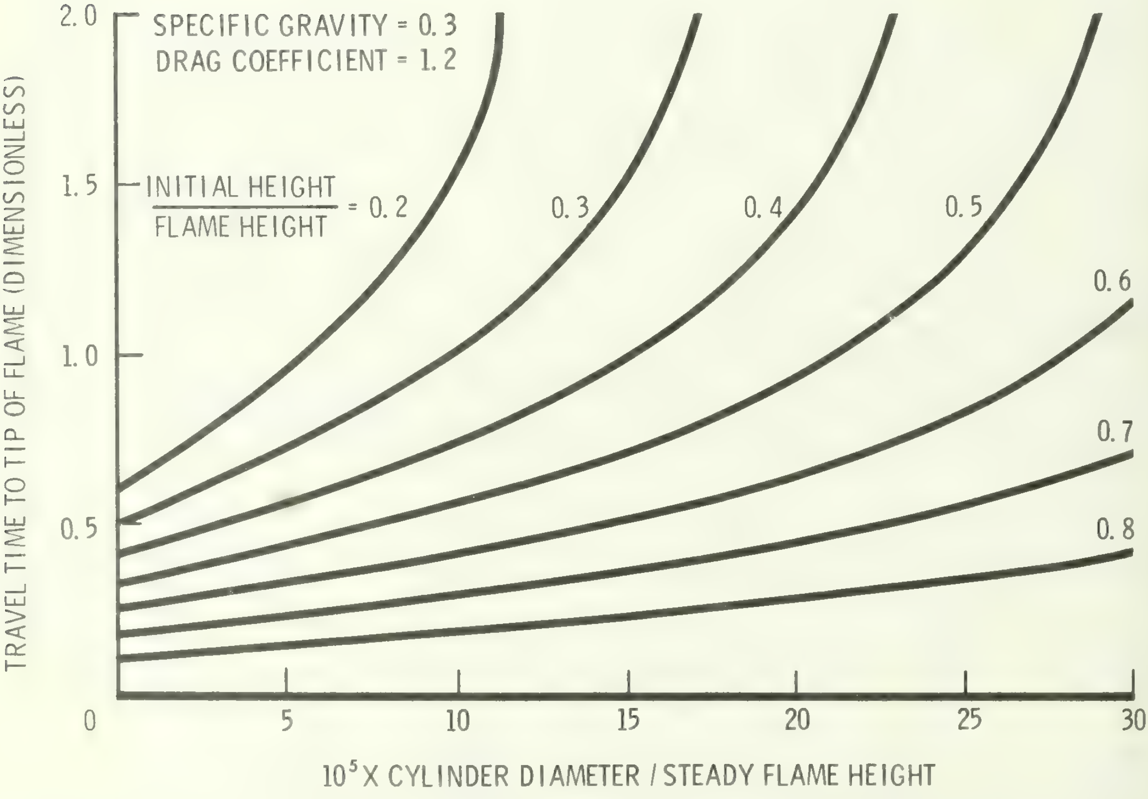


*Figure D-3.--Approximate travel time for wood cylinder lifted by flame.*

Since

$$v_o/w_F = B(D/z_F)^{1/2} \qquad \text{(D28)}$$

and

$$(1.4)^2 \doteq 2, \qquad \text{(D29)}$$

this can be written as

$$w_F t_t/2z_F \doteq 0.2 + B\left(\frac{D}{z_F}\right)^{1/2}\left\{1 + B\left(\frac{D}{z_F}\right)^{1/2} \ln\left(1 + 1/\left(1 - B\left(\frac{D}{z_F}\right)^{1/2}\right)\right)\right\}. \qquad \text{(D30)}$$

This expression, like equation (D17), gives travel times near unity over the pertinent range of $D/z_F$. Figure D-4 is a graph of equation (D30).

To the travel times given in figures D-3 and D-4 must be added a travel time within the plume. This last time will be a function of the height to which the particle is lifted. Then by comparing the time it takes the particle to reach a particular height with the time the flow structure will persist to that height we can derive the maximum achievable height as a function of particle size.

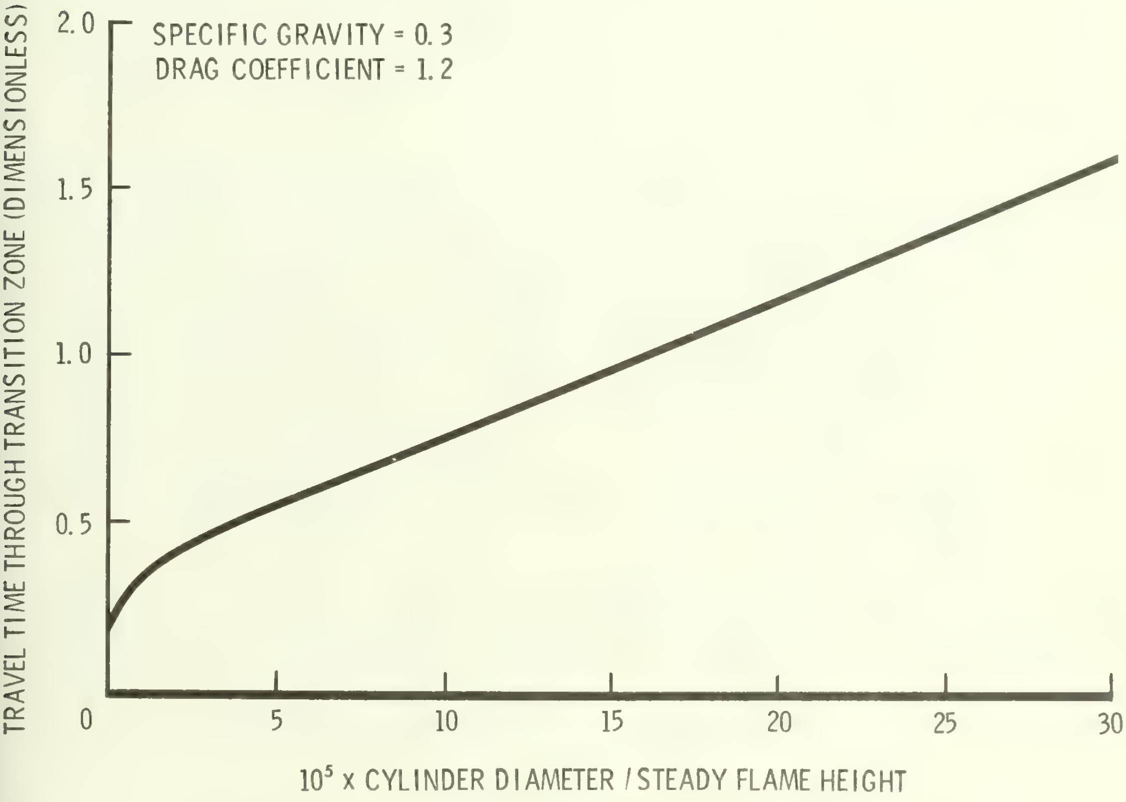


*Figure D-4.--Approximate travel time for small cylinder through transition zone between tip of flame and buoyant plume.*

The flight of the particle in the buoyant plume is approximated here by

$$\frac{dz}{dt} = w - v_{op} \tag{D31}$$

where, from appendix B, the gas velocity is approximated by

$$w \doteq w_F(a/(b + z/z_F))^{1/2} \tag{D32}$$

with

$$a = 5.963 \tag{D33}$$

$$b = a - 1.4 = 4.563. \tag{D34}$$

The particle terminal velocity in the plume, $v_{op}$, is related to that in the flame, $v_o$, by

$$v_{op} \doteq 0.8v_o = 0.8Bw_F(D/z_F)^{1/2}. \tag{D35}$$

Again normalizing the particle height by the steady flame height and the time by the characteristic gas travel time through the flame, the time, $t_p$, required for a given particle to travel from the base of the plume ($1.4z_F$) to the height z can be written as

$$\frac{w_F t_p}{2z_F} = \frac{1}{2}\int_{a-b}^{z/z_F}\left(\left(\frac{a}{b + x}\right)^{1/2} - 0.8v_o/w_F\right)^{-1}dx. \tag{D36}$$

The result of the indicated integration in (D36) can be expressed conveniently in terms of the variable r, where

$$r = ((b + z/z_F)/a)^{1/2}. \tag{D37}$$

In terms of r, equation (D36) gives

$$\frac{w_F t_p}{2z_F} = \frac{a}{\left(0.8\frac{v_o}{w_F}\right)^3}\left\{\ln\left(\frac{1 - 0.8v_o w_F}{1 - 0.8rv_o/w_F}\right) - \left(0.8\frac{v_o}{w_F}\right)(r - 1) - \frac{1}{2}\left(0.8\frac{v_o}{w_F}\right)^2(r^2 - 1)\right\}. \tag{D38}$$

Again, using (D18) with a value of 40 for B, this formula can be used to calculate particle travel time in the plume. By combining the times given by equations (D38), (D30), and (D17) one obtains the total travel time from initial particle height, $z_o$, to the "final" height, z.

The contribution to this total time from the variation in initial particle height (figure D-3) complicates the calculation and presentation of the total time of travel. The refinement of a continuously variable initial height is clearly not warranted by the precision of the models presented here, either. So as a compromise between unwarranted generality and oversimplification, four representative values of $z_o/z_F$ were chosen for display and further computation. Because the initial height of a firebrand particle would be no greater than the height of a tree contributing to the flame and because it has been assumed that the base of the flame is at one-half the tree height, the following representative values were chosen:

| | | | | |
|---|---|---|---|---|
| Tree Height/Flame Height (Range) | $\leq 0.5$ | .5-1.0 | 1.0-1.5 | $\geq 1.5$ |
| Particle Initial Height/Flame Height (Range) | $\leq 0.25$ | .25-.5 | .5-.75 | $\geq .75$ |
| Nominal Value of $z_o/z_F$ | 0.2 | 0.4 | 0.6 | 0.8 |

These values probably typify the range of conditions to be encountered when single trees or groups of trees "torch out."

Using the nominal values for $z_o/z_F$ in the tabulation above, figures D-5 hrough D-8 were constructed by adding the travel times from equations (D17), D30), and (D38). Because the phase of travel from initial height to flame ip is a strong function of particle diameter for small values of $z_o/z_F$ (i.e., or tall flames) the "resolution" in terms of $D/z_F$ varies from one figure to nother.

These figures provide the basis for a graphical solution of the firebrand ifting problem. The trajectories described by these four figures require that he gas flow exist over the height and time span indicated. So where the line escribing the trajectory of the last bit of flame gas crosses one of the paricle trajectories, it marks the maximum height achievable by a particle of the ze associated with the intersected trajectory. The time required for the colapse of the flame/plume structure, in dimensionless units, is readily available rom the equations already presented (D17, D30, and D38). One merely takes the imiting forms of these equations when the particle diameter approaches zero. oing so gives the following results:

Time to travel from flame base ($z_o = 0$) to flame tip = $t_1$ (eq. D17)

$$t_1 = \lim_{\substack{v_o \to 0 \\ z_o \to 0}} \left(1 - \left(\frac{z_o}{z_F}\right)^{1/2} + \frac{v_o}{w_F} \ln\left(\frac{1 - v_o/w_F}{(z_o/z_F)^{1/2} - v_o/w_F}\right)\right) = 1. \qquad \text{(D39)}$$

Time to travel through "transition zone" = $t_2$ (eq. D30)

$$t_2 = \lim_{D \to 0} \left\{0.2 + B\left(\frac{D}{z_F}\right)^{1/2} \left(1 + B\left(\frac{D}{z_F}\right)^{1/2} \ln\left(1 + 1/\left(1 - B\left(\frac{D}{z_F}\right)^{1/2}\right)\right)\right)\right\} = 0.2. \qquad \text{(D40)}$$

Time to travel from plume base to height $z = t_3$. For this expression it is simpler to approach the limit in equation (D36) before integrating:

$$t_3 = \lim_{v_o \to 0} \frac{1}{2}\int_{a-b}^{z/z_F}\left(\left(\frac{a}{b+x}\right)^{1/2} - 0.8\,\frac{v_o}{w_F}\right)^{-1} dx = \frac{1}{2}\int_{a-b}^{z/z_F}\left(\frac{b+x}{a}\right)^{1/2} dx \qquad \text{(D41)}$$

$$t_3 = \frac{a}{3}\left\{\left(\frac{b + z/z_F}{a}\right)^{3/2} - 1\right\}. \qquad \text{(D42)}$$

The total time for which the flow structure exists to height z, then is given by $t_T$, where

$$t_T = t_o + t_1 + t_2 + t_3 = t_o + 1.2 + \frac{a}{3}\left\{\left(\frac{b + z/z_F}{a}\right)^{3/2} - 1\right\}, \qquad \text{(D43)}$$

and $t_o$ is the period of steady burning of the tree crown(s) normalized by the characteristic time $2z_F/w_F$. Equation (D43) is plotted[11] in figure D-9 on the same scale as figures D-5 through D-8, using various values for $t_o$. By overlaying figures D-5 through D-8 on this graph, one can derive the maximum particle height as a function of particle size and steady flame duration, $t_o$.

Alternatively, one may insert the values of $t_T$ and $z/z_F$ obtained from the particle trajectory figures into equation (D43) and derive the required flame duration, $t_o$. Using intermediate values not necessarily displayed in figures D-5 through D-8, figures D-10 through D-13 were derived in this way. These figures permit the final step in the long procedure outlined here--fixing the maximum height of viable firebrands.

Overlaid on these figures is the dashed line relating the initial diameter of a wood particle and the maximum height through which it may fall and yet be burning (glowing) on impact. This relationship, based on the wind model presented in appendix E and trajectory analysis described in appendix F, is:

$$\max(z) = 0.39 \times 10^5 D. \qquad \text{(D44)}$$

The initial particle height must be added to the height increment gained in the flame and plume, so the dashed line must intercept the solid lines at the points where

$$z/z_F = 0.39 \times 10^5 (D/z_F) - z_o/z_F. \qquad \text{(D45)}$$

The final result, a plot of the maximum viable particle height versus flame duration for the four initial heights, is given as figure 7 in the text.

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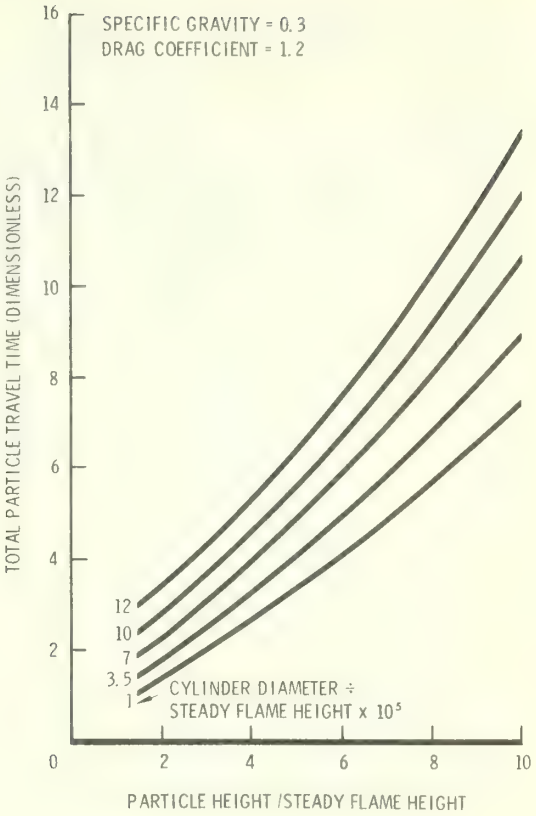
[11] The plot is readily extended below $z/z_F = 1$; the functional form of $t_1$ for $z < z_F$ is a square root.

*Figure D-5.--Total travel time for wood cylinder lifted by flame into buoyant plume. Initial particle height = 0.2 x steady flame height.*



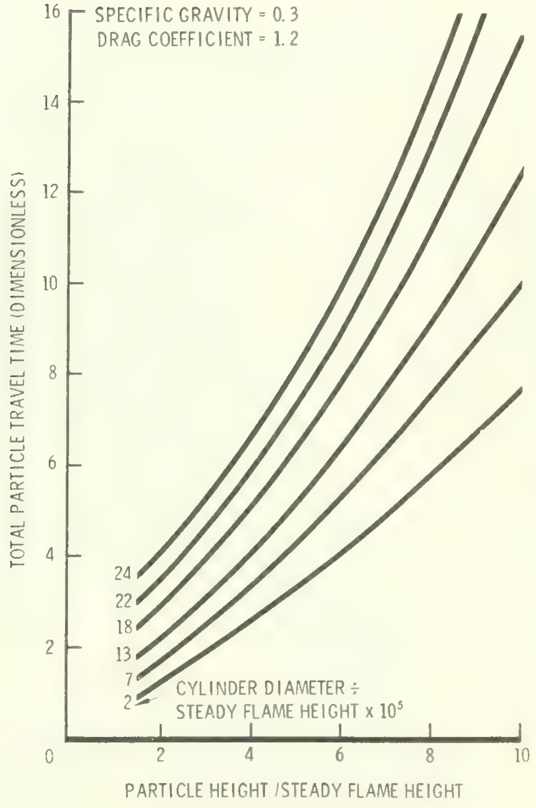


*Figure D-6.--Total travel time for wood cylinder lifted by flame into buoyant plume. Initial particle height = 0.4 x steady flame height.*

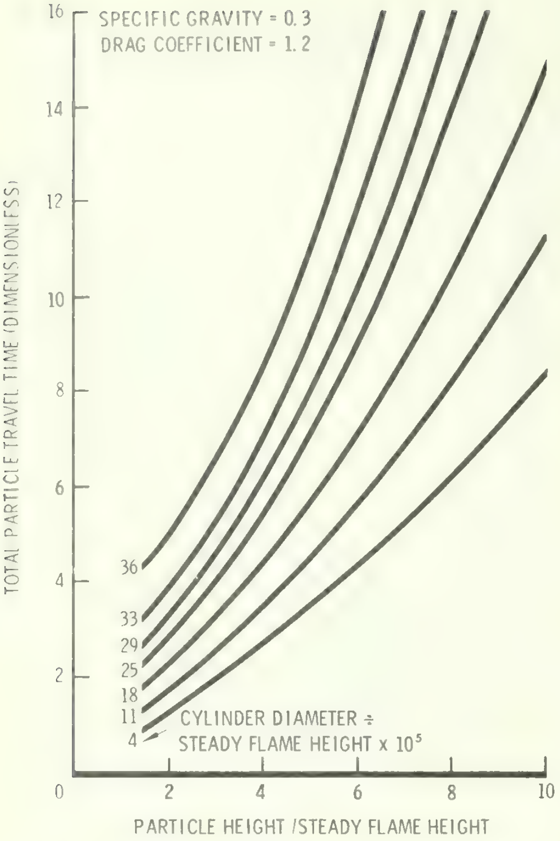


Figure D-7.--Total travel time for wood cylinder lifted by flame into buoyant plume. Initial particle height = 0.6 x steady flame height.

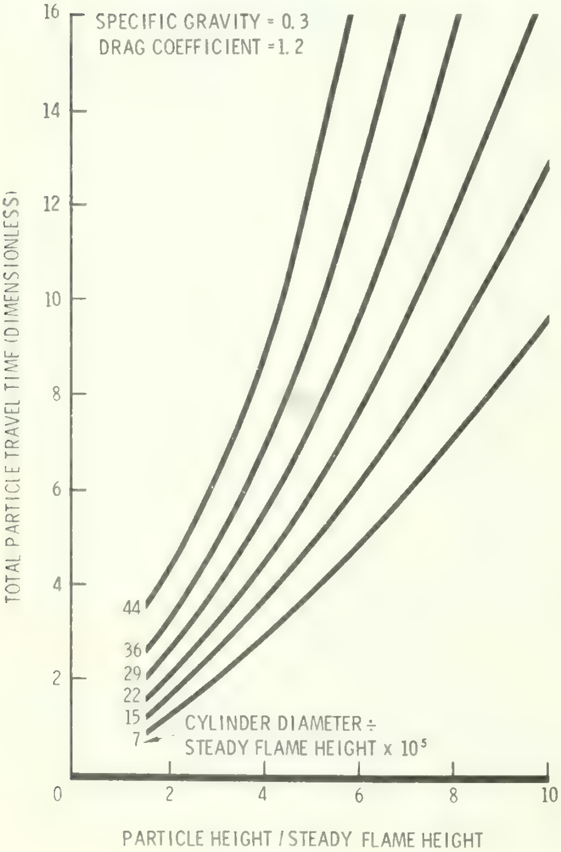
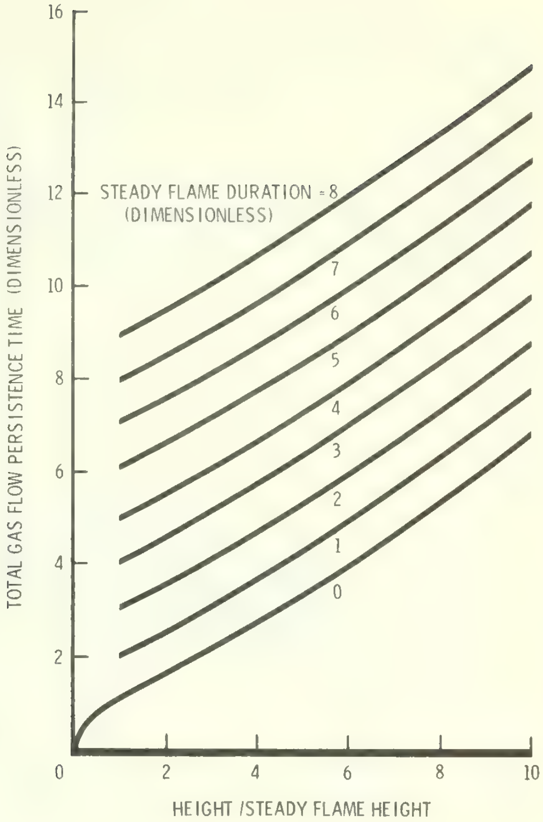
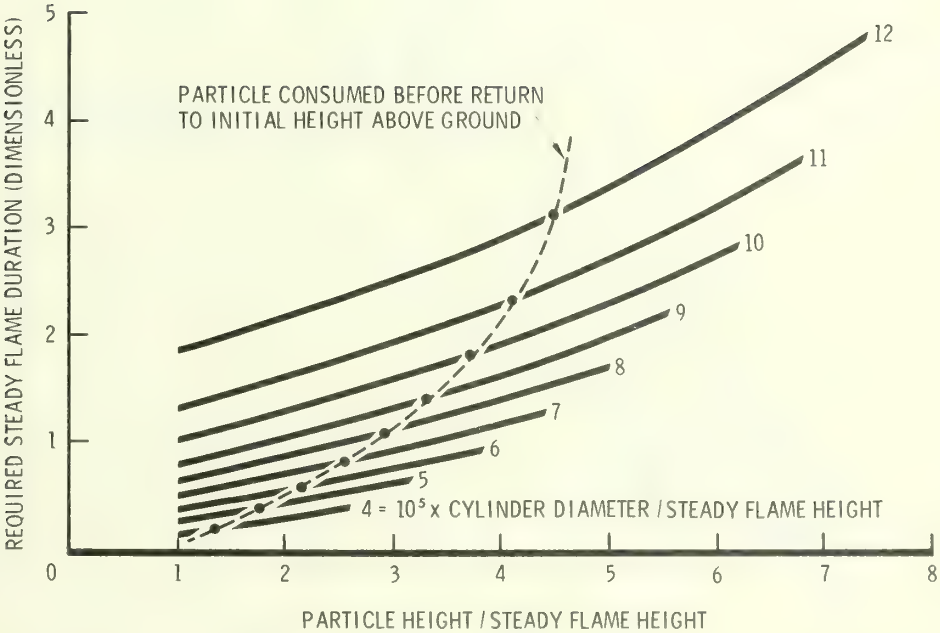


Figure D-8.--Total travel time for wood cylinder lifted by flame into buoyant plume. Initial particle height = 0.8 x steady flame height.

*Figure D-9.--Total gas flow persistence time for buoyant plume above flame.*





*gure D-10.--Flame duration required to lift wood cylinder to various heights, starting from 0.2 x steady flame height.*

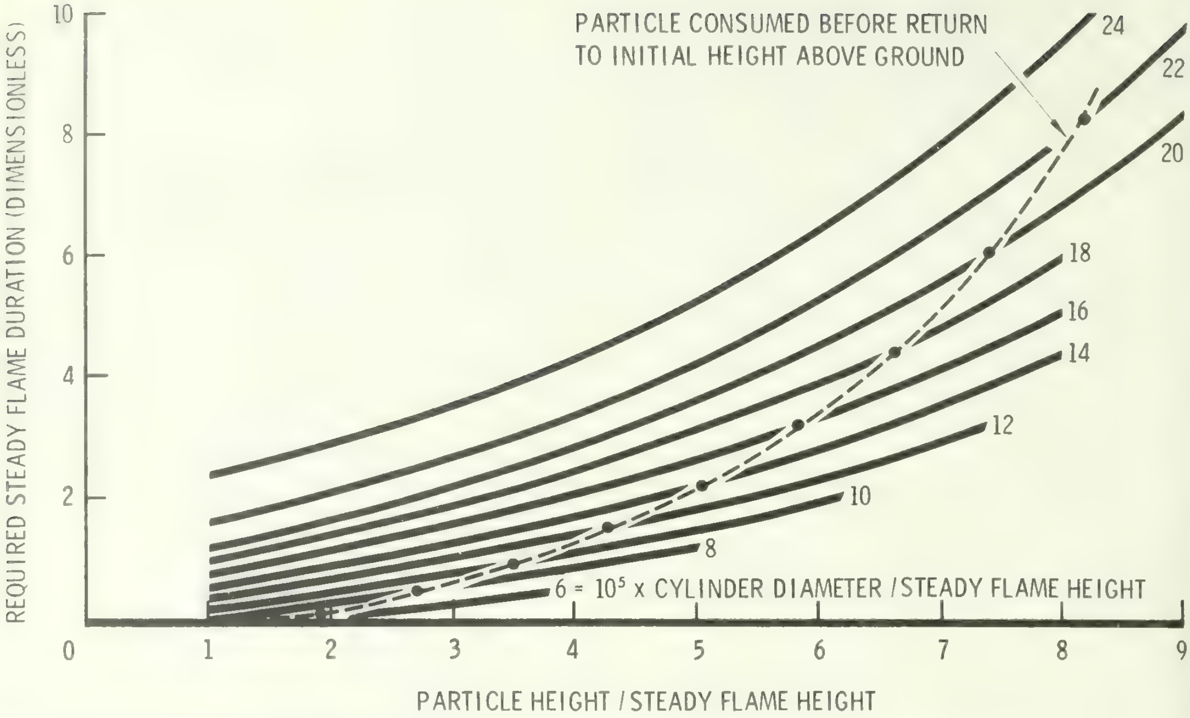


Figure D-11.--Flame duration required to lift wood cylinder to various heights, starting from 0.4 x steady flame height.

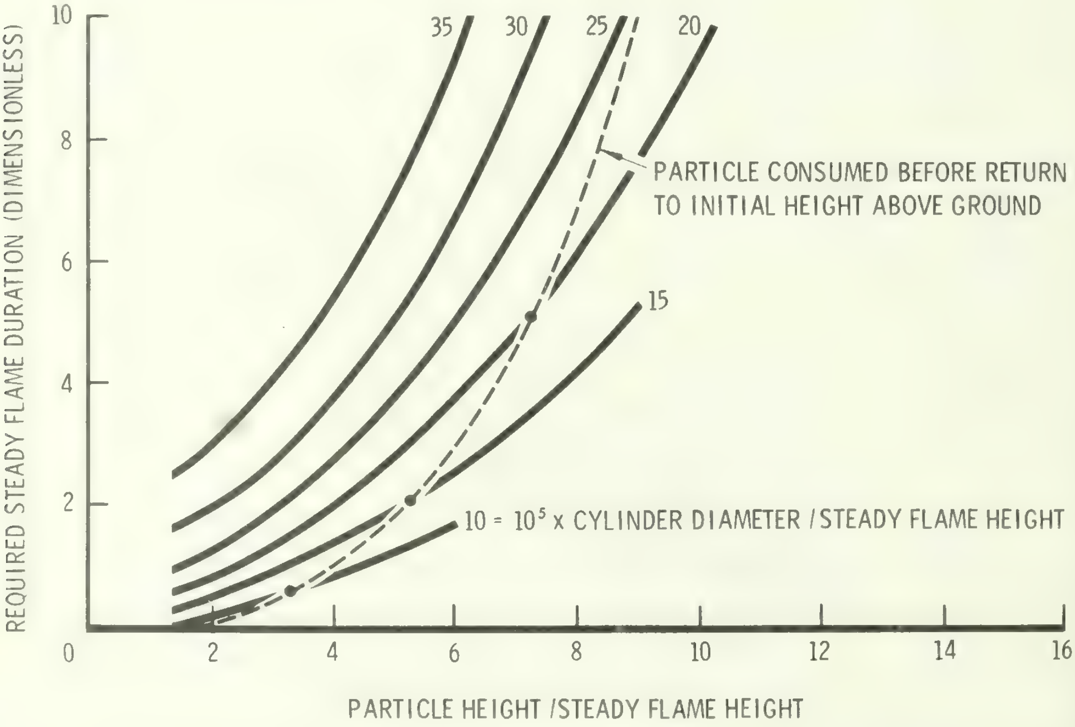
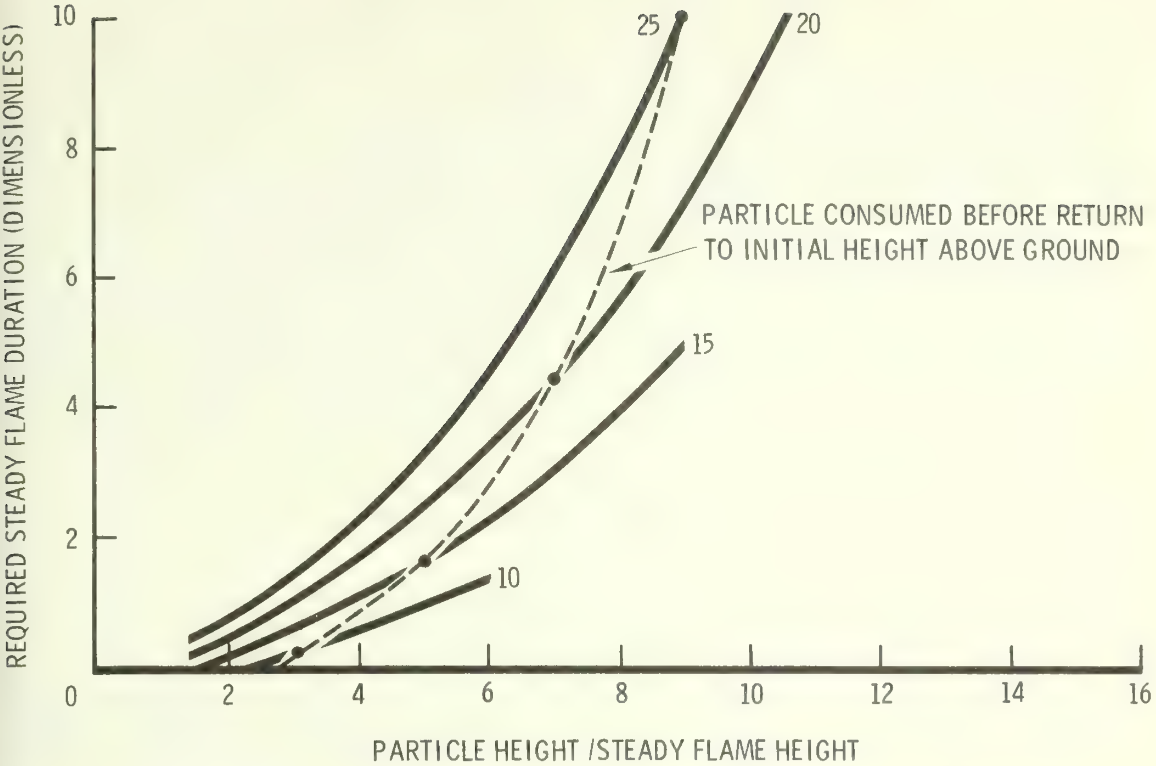


Figure D-12.--Flame duration required to lift wood cylinder to various heights, starting from 0.6 x steady flame height.



*igure D-13.--Flame duration required to lift wood cylinder to various heights, starting from 0.8 x steady flame height.*

# APPENDIX E: A CRUDE MODEL FOR SURFACE WIND OVER ROUGH TERRAIN

In order to calculate the distance that a firebrand might be carried by the wind, it is necessary to describe the wind field in detail. Such a description is clearly beyond the state of the art of meteorology when the problem is stated in general terms. That is, the details of the wind velocity pattern over rough terrain for arbitrary atmospheric conditions are not predictable at the present time. But since we are concerned only with making rather crude "limiting" calculations, it is sufficient for the purpose at hand to describe the general features of the flow field in some typical situations. The crude model should reflect the influence of the terrain and the roughness of the surface cover on the windspeed, but it is not necessary that the model be forecastable or even relatable to atmospheric transport processes. It need only be descriptive, and correct in the sense and approximate magnitude of factors that influence the wind pattern.

Two idealized situations are used here to typify the spotting problem:

1. The terrain can be considered to be flat in the direction of the prevailing wind.

2. The wind blows directly across a "smooth" ridge/valley profile that represents the major terrain relief in the area of concern.

These two situations obviously do not exhaust the possibilities, but until the entire spot fire model is validated to some degree in these easily described situations there seems little point to complicating the picture further.

The first case is intended to represent not only genuinely flat or gentle terrain, but airflow up or down drainages. The second case is intended to represent a typical fire control problem--spotting over a ridgetop or valley floor fuel break.

For the "flat terrain" case we shall use only a horizontal wind component. The windspeed near the surface, above the canopy of a forested area, is well described by a logarithmic profile (Sutton 1953; Marunich 1975):

$$U = (U_*/K)\ln(z/z_o) \qquad \text{(E1)}$$

where

U = horizontal windspeed (short term average)
z = height above ground
$z_o$ = "roughness length," a linear scale associated with the turbulent transport of shear stress
$U_*$ = "friction velocity," a characteristic windspeed
K = von Karman's constant, usually reckoned at 0.4.

Data presented by Marunich (1975) and Tanner and Pelton (1960) indicate that the roughness length is related to tree height for wind over a uniform-height forest canopy. These data provide the following values:

$$z_o = 0.1313H \qquad \text{(E2)}$$

$$U_* = 0.16U\Big|_{z=1.6H} \qquad \text{(E3)}$$

where H = tree height.

Other surface covers give rise to other (smaller) friction lengths (Sutton 1953).

Referring velocities to the value just at treetop height, $U_H$, gives

$$U = U_H \ln(z/0.1313H)/\ln(1/0.1313) = 0.493U_H \ln(z/0.1313H). \qquad \text{(E4)}$$

This is the form used in the calculation of firebrand transport presented in the text.

For the second case, the matter is not so simple. In this case the velocity of the wind in the vertical direction (W) must be taken into account, as well as the variation of windspeed with height (z) and horizontal distance (X). It has often been noted that windspeed is greater at ridgetops than at midslope, and greater there than on the valley floor (Sutton 1953). The modeling of these variations has met with little success (Brown 1974) and is the subject of current research and development effort (Fosberg and others 1976; Ryan 1977).

Here we wish to capture only the gross features of such variations in a simple form. To do this we posit an oversimplified physical picture of the flow field over the rough terrain. The physical assumptions of this model are:

1. There exists an inviscid flow field trapped between an isobar at (constant) height $z_G$ and a friction-dominated surface layer of height $z_{FR}(X)$.

2. The flow fields in both the inviscid upper layer and the friction layer are two-dimensional. That is, velocity exists in the X direction (U) and the z direction (W) only.

3. The friction layer boundary, $z_{FR}(X)$, is a streamline below which the horizontal velocity is logarithmic in z with a constant roughness length, $z_o$. No stability correction is applied.

4. The flow satisfies the incompressible continuity equation everywhere and air density variations are neglected.

5. Horizontal velocity is independent of height in the inviscid layer. In crude form, then, this model mimics some major features of Fosberg's (1976) model. In the model presented by Fosberg it is suggested that the "lid" height, $z_G$, should be taken to be 1.5 to 2.0 km above the mean height of the terrain. For the purpose of presenting numerical results in this paper we take $z_G$ to be 6,000 ft (about 1.8 km) above the mean terrain height.

The flow field resulting from the above assumptions can be derived in a straightforward way. First, in the inviscid upper layer we have:

$$U(X)\cdot\left(z_G - z_{FR}(X)\right) = \text{constant} = V_G. \qquad \text{(E5)}$$

From the continuity equation

$$\frac{\partial U}{\partial X} + \frac{\partial W}{\partial z} = 0 \qquad \text{(E6)}$$

this implies a vertical velocity distribution

$$W(X,z) = -\left[V_G z/(z_G - z_{FR})\right]^2 \frac{dz_{FR}}{dX} + f(X). \tag{E7}$$

The arbitrary function f(X) is determined by matching the upper boundary condition that $z_G$ is constant, a horizontal streamline:

$$W(X,z) = \left[\frac{V_G(z_G - z)}{(z_G - z_{FR})^2}\right]\frac{dz_{FR}}{dX} = U\left[\frac{z_G - z}{z_G - z_{FR}}\right]\frac{dz_{FR}}{dX}. \tag{E8}$$

In the friction layer between the terrain surface, $z_T(X)$, and the streamline $z_{FR}(X)$, we have

$$U = \frac{U_*(X)}{K} \ln\left(\frac{z - z_T(X)}{z_o}\right). \tag{E9}$$

The arbitrary friction velocity allows the matching of horizontal windspeed at the friction layer upper boundary, with the result:

$$U = \frac{V_G}{z_G - z_{FR}(X)} \ln\left(\frac{z - z_T(X)}{z_o}\right) \Big/ \ln\left(\frac{z_{FR}(X) - z_T(X)}{z_o}\right). \tag{E10}$$

The vertical velocity field in the friction layer is to be found by integrating the continuity equation. The result can be abbreviated as:

$$W = U\frac{dz_T}{dX} - z_o \frac{dF}{dX} \int_1^{(z-z_T)/z_o} \ln y \, dy, \text{ where} \tag{E11}$$

$$F(X) = \frac{V_G}{z_G - z_{FR}(X)} \ln\left(\frac{z_{FR} - z_T}{z_o}\right). \tag{E12}$$

Equation (E11) satisfies the boundary condition at the terrain surface ($z = z_T + z_o$); by imposing the boundary condition at the top of the friction layer

$$W(X,z_{FR}) = U(X,z_{FR})\frac{dz_{FR}}{dX} \tag{E13}$$

we obtain an equation describing the dependence of $z_{FR}$ on $z_T$. This equation is

$$\frac{dz_{FR}}{dX} = \frac{dz_T}{dX} - z_o(z_G - z_{FR}) \int_1^{\frac{z_{FR}-z_T}{z_o}} \ln y \, dy \, \frac{d}{dX}\left((z_G - z_{FR}) \ln\left(\frac{z_{FR} - z_T}{z_o}\right)\right)^{-1}. \tag{E14}$$

The dependence of $z_{FR}$ on $z_T$ can best be deduced by relating two intermediate variables:

$$f = (z_{FR} - z_T)/z_o \tag{E15}$$

$$g = (z_G - z_{FR})/z_o \tag{E16}$$

$$\frac{df}{dX} = -g \int_1^f \ln y \; dy \; \frac{d}{dX}\left(\frac{1}{g \ln f}\right). \tag{E17}$$

Carrying out the indicated differentiation and rearranging terms this becomes an easily integrated form:

$$\ln f \frac{df}{dX} \Big/ \int_1^f \ln y \; dy - \frac{1}{f}\frac{df}{dX} \Big/ \ln f = \frac{dg}{dX} \Big/ g \tag{E18}$$

$$\ln \left\{ \int_1^f \ln y \; dy \right\} - \ln \left\{ \ln f \right\} = \ln g + \text{constant} \tag{E19}$$

or

$$\int_1^f \ln y \; dy \Big/ g \ln f = \text{constant} = C. \tag{E20}$$

This last form is most revealing if cast in terms of the ratio of friction layer thickness to total (friction plus inviscid) layer thickness

$$\Phi = \frac{z_{FR} - z_T}{z_G - z_T} = f/(f + g) \tag{E21}$$

$$\Phi = \Big(C - 1/(g \ln f)\Big) \Big/ \Big(C + 1 - (1 + \frac{1}{g})/\ln f\Big). \tag{E22}$$

Because both f and g are large numbers relative to unity, equation (E22) provides the extremely useful result, that $\Phi$ may be considered to be constant. From equation (E20) it is clear that C (and hence $\Phi$) is a small number. In fact, Sutton (1953) cites data taken over flat terrain that indicate $\Phi = 0.12$. Brown (1974) "splices" friction layer profiles to Ekman layer profiles and asserts that this layer depth ratio should be of the order of 0.1. In numerical results presented herein we have used $\Phi = 0.12$.

A further simplification obtains from this result and equation (E11). Note from (E11) that the relationship between W and U in the friction layer varies between the limits

$$W = U \frac{dz_T}{dX} \quad \text{at } z = z_T + z_o \tag{E23}$$

and

$$W = U \frac{dz_{FR}}{dX} = (1 - \Phi) U \frac{dz_T}{dX} \quad \text{at } z = z_{FR}. \tag{E24}$$

Because the "error" is so slight and the simplification is so great in the particle trajectory equations, the further approximation is made that the streamlines follow the terrain contour in the friction layer:

$$W \doteq U \frac{dz_T}{dX}. \qquad \text{(E25)}$$

From equations (E5), (E8), and (E10) it is also clear that the friction layer equations for U and W can be extended into the inviscid zone for a distance equal to a large fraction of the friction layer height before significant error accumulates. This approximation is also invoked in deriving the firebrand trajectories in appendix F.

The variation of horizontal wind velocity with distance (U(X)) is plotted in figure E-1 for terrain described by a sinusoid:

$$z_T(X) = a \sin (\pi X/X_o). \qquad \text{(E26)}$$

The total terrain relief, 2a, is a parameter for these curves. The curves plotted are given by equation (E10) with

$$(z_{FR} - z_T)/(z_G - z_T) = 0.12 \qquad \text{(E27)}$$

and $z_G$ equal to 6,000 ft above the average value of $z_T$. This plot shows that for a ridge-to-valley elevation change of 2,000 ft, the velocity at a constant height above the terrain differs by about 40 percent between ridge and valley locations. It is this variation of horizontal windspeed with horizontal distance that causes the differences in potential spotting distances shown in the graphs in the text.

To facilitate transformation of windspeed measurements or forecasts (to establish the midslope reference value of treetop height wind), the variation of horizontal windspeed with terrain elevation is graphed in the text.

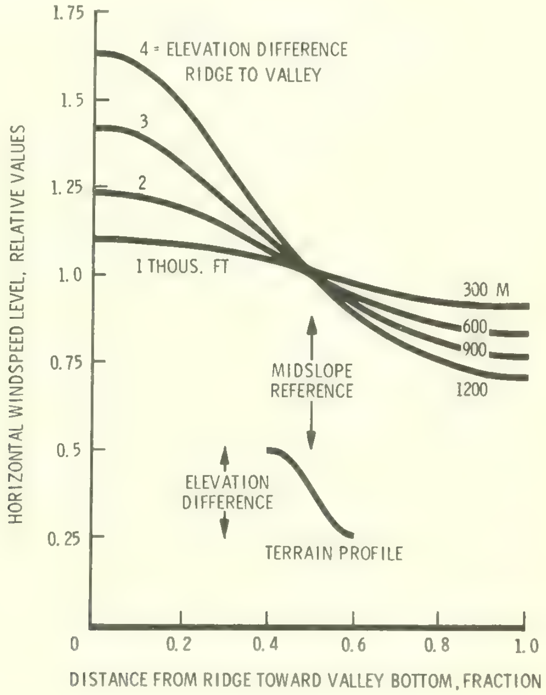


*Figure E-1.--Variation of horizontal windspeed at constant height above terrain for flow across ridge and valley. Model results for sinusoid terrain profile and uniform forest cover, 100 ft (30 m) trees.*

# APPENDIX F: FIREBRAND TRAJECTORIES

In this appendix we combine the model for the burning of wood cylinders (appendix C) and the model for the windspeed over rough terrain (appendix E) to calculate the maximum possible travel distance of such particles. This is done in two steps. First we compute the maximum spot fire distance over flat terrain, then we calculate a correction factor for rough terrain.

Using the approximation that the particle everywhere has a relative velocity in the vertical direction equal to its instantaneous terminal fall velocity (appendix D) we can write the equations of motion for the burning firebrand as follows:

$$\frac{dX}{dt} = U(X,z) \tag{F1}$$

$$\frac{dz}{dt} = W(X,z) - v_o(t). \tag{F2}$$

Here we use the symbols

$X$ = horizontal distance
$z$ = vertical distance
$t$ = time (since start of firebrand fall)
$U$ = horizontal windspeed
$W$ = vertical windspeed
$v_o$ = particle terminal fall velocity, a function of $t$.

The fact that the relative velocity of the particle with respect to the wind is everywhere equal to $v_o$ allows us to obtain the time dependence of $v_o$ directly. From appendix C we have the model

$$\frac{d}{dt}(\rho_s D) = -K\rho_a v_o \tag{F3}$$

here

$K = 0.0064$
$\rho_s$ = density of wood cylinder
$D$ = mean diameter of wood cylinder
$\rho_a$ = density of air
$v_o$ = relative velocity of cylinder and air (here equal to terminal velocity).

But since the terminal velocity is given by

$$v_o = (\pi g \rho_s D / 2 C_D \rho_a)^{1/2} \tag{F4}$$

here

$g$ = acceleration of gravity
$C_D$ = drag coefficient (1.2)

quation (F3) can be written in terms of $v_o$:

$$\rho_s D = 2C_D \rho_a v_o^2 / \pi g \tag{F5}$$

$$(4C_D \rho_a v_o / \pi g)\frac{dv_o}{dt} = -K\rho_a v_o \tag{F6}$$

$$\frac{dv_o}{dt} = -K\pi g/4C_D . \tag{F7}$$

This leads immediately to a most useful result:

$$v_o(t) = v_o(0)\big(1 - K\pi gt/4C_D v_o(0)\big) . \tag{F8}$$

In other words, the particle slows down its relative fall velocity linearly in time. During the time it burns out, it moves a distance $\Delta z$ relative to the air in which it is borne along, where

$$\Delta z = \frac{1}{2} v_o(0)\left[\frac{4C_D v_o(0)}{K\pi g}\right] = (\rho_s D)_o / K\rho_a \tag{F9}$$

and

$(\rho_s D)_o$ = the initial value of $(\rho_s D)$.

Because, according to the wind model derived in appendix E, streamlines near the surface are parallel to the terrain surface, this "fall distance" is a constant of the trajectory and is equal to the initial height of the particle if the particle burns out on returning to the surface. This fact was used in appendix D to identify those particles that have the greatest potential spot distance.

Using the shorthand notation

$$\tau = 4C_D v_o(0)/K\pi g \tag{F10}$$

equation (F2) can be written

$$\frac{dz}{dt} = W(X,z) - v_o(0)(1 - t/\tau) . \tag{F11}$$

### *Flat Terrain Spot Distance*

Equations (F1) and (F11), with U given by a logarithmic function of z and W equal to zero, describe the flight of a firebrand over flat terrain:

$$\frac{dX}{dt} = \big(U_*/K\big)\ln(z/z_o) \tag{F12}$$

$$\frac{dz}{dt} = -v_o(0)(1 - t/\tau) . \tag{F13}$$

The logarithmic profile does not accurately describe windspeed variation below treetop height. Although such windspeed variations have been measured many times (Baynton 1965; Bergen 1971; Fons 1940; Gisborne 1941; Leonard and Federer 1973; Martin 1971; Marunich 1975; Oliver 1971; Raynor 1971), no universal rule is applicable because of the many factors that can influence the wind field structure within and below the crown layer. One approximation for the purpose at hand would be to use a constant windspeed below treetop height. This would give a maximum spot fire distance, but perhaps one unrealistically large. Another approach would be to consider the crown layer as a mechanical obstacle to the flight of a firebrand and set the windspeed to zero below treetop height. Such an approximation would tend to give a lower bound to the spot fire distance. A compromise that interpolates between these extremes is to extend the logarithmic profile below treetop height all the way to zero velocity. This is the alternative used here. The effect of this assumption is assessed later in this appendix.

Denoting treetop height by H and the horizontal windspeed at that height by $U_H$, equation (F12) can be written as

$$\frac{dX}{dt} = U_H \ln(z/z_o)/\ln(H/z_o). \qquad \text{(F14)}$$

The friction length, $z_o$, is set to 0.1313H for the calculation of numerical results. The treetop height, and hence $z_o$, is considered to be constant over the range of particle travel.

Equation (F13) can be integrated to give the particle height as a function of time:

$$z(t) = z(0) - v_o(0)\tau\left(t/\tau - \frac{1}{2}(t/\tau)^2\right). \qquad \text{(F15)}$$

Because we seek the maximum spot fire distance, the particle should just be consumed at the time of contact with the ground, or

$$z(\tau) = 0 \qquad \text{(F16)}$$

and so

$$z(t) = z(0)(1 - t/\tau)^2. \qquad \text{(F17)}$$

Using this result in equation (F13) and dividing equation (F14) by the resulting xpression gives the equation for the particle's distance of travel (X) as a unction of its height (z):

$$\frac{dX}{dz} = -\left(\frac{U_H}{v_o(0)}\right)\left(\frac{z(0)}{z}\right)^{1/2} \ln(z/z_o)/\ln(H/z_o). \qquad \text{(F18)}$$

his equation is readily integrated to give the maximum horizontal distance X*. When ormalized by the tree height the result is:

$$X^*/H = \frac{4U_H}{v_o(0)} \; \frac{(z_o z(0))^{1/2}}{H \ln(H/z_o)} \left\{\left(\frac{z(0)}{z_o}\right)^{1/2}\left(\frac{1}{2} \ln\left(\frac{z(0)}{z_o}\right) - 1\right) + 1\right\}. \qquad \text{(F19)}$$

Since

$$\ln(H/z_o) = -\ln(0.1313) = 2.03, \tag{F20}$$

this expression is very well approximated by the form

$$X^*/H \doteq \frac{2U_H}{v_o(0)} \left(\frac{z(0)}{H}\right)^{1/2} \left\{(0.1313)^{1/2} + \frac{1}{2}\left(\frac{z(0)}{H}\right)^{1/2} \ln\left(\frac{z(0)}{H}\right)\right\}. \tag{F21}$$

If the integral on z had been terminated at H rather than at $z_o$ (zero windspeed below treetop height) the term $\sqrt{0.1313}$ would be missing from this expression. And if the windspeed were set to a constant for z less than H, the term $\sqrt{0.1313}$ would be replaced by unity. Figure F-1 shows how the results would change, using the constant windspeed (maximum range) assumption as a reference condition for comparison.

Using equation (F9) for $v_o(0)$ in terms of $z(0)$ ($= \Delta z$) and using numerical values for the constants gives the equation plotted as a nomograph in the text:

$$X^* = 21.9U_H\left(\frac{H}{g}\right)^{1/2} \left\{0.362 + \left(\frac{z(0)}{H}\right)^{1/2} \frac{1}{2} \ln\left(\frac{z(0)}{H}\right)\right\}. \tag{F22}$$

This result is more cogent than it may appear at first, since a multiplying factor can extend the validity of the expression to uneven terrain.

### *Uneven Terrain Spot Distance*

The flight of a firebrand over uneven terrain is described by equations (F1) and (F16) when the wind field is related to the terrain surface. Using the wind model described in appendix E and especially the approximation that the streamlines parallel the terrain, we can write the equation for particle height as a function of time:

$$\frac{dz}{dt} = U \frac{dz_T}{dX} - v_o(t) \tag{F23}$$

where $z_T(X)$ = terrain height at location X.

Because the particle travels horizontally at speed U, the height of the particle above ground obeys the simple equation

$$\frac{d}{dt}(z - z_T) = -v_o(t) = -v_o(0)(1 - t/\tau). \tag{F24}$$

The simplification made possible by this result is enormous. Because the horizontal windspeed is related to the height above the local terrain:[12]

$$\frac{dX}{dt} = U(X,z) = \frac{v_G/\ln\left(\phi\,\dfrac{z_G - z_T}{z_o}\right)}{(1 - \phi)(z_G - z_T)} \ln\left(\frac{z - z_T}{z_o}\right) \tag{F25}$$

---

[12] See appendix E for definition of symbols $\phi$, $z_G$, and $v_G$.

and since

$$z - z_T = \big(z(0) - z_T(X = 0)\big)(1 - t/\tau)^2 = z^0(1 - t/\tau)^2 \tag{F26}$$

equation (F23) is essentially the same as equation (F14). If the treetop height windspeed, $U_H$, is considered to be a function of horizontal position, the equations are identical. The integral form for the maximum spot distance is obtained as before. Using equation (F26) in (F24) and dividing (F25) by the result yields:

$$\frac{dX}{d(z - z_T)} = -\frac{\big(v_G/v_o(0)\big)\ln(H/z_o)\cdot\big(z^0/(z - z_T)\big)^{1/2}\ln\big((z - z_T)/z_o\big)}{(1 - \phi)(z_G - z_T)\ln\big(\phi(z_G - z_T)/z_o\big)\ln(H/z_0)}. \tag{F27}$$

The integral of the function of $(z - z_T)$ on the right gives a function of initial particle height above the ground $(z^0)$ and tree height that is identical to the previous case. Hence we have:

$$\frac{1 - \phi}{v_G \ln \frac{H}{z_o}} \int_0^{X^*} (z_G - z_T)\ln\left(\frac{\phi(z_G - z_T)}{z_o}\right)dx = \frac{2H}{v_o(0)}\left(\frac{z^0}{H}\right)^{1/2}\left\{0.362 + \frac{1}{2}\left(\frac{z^0}{H}\right)^{1/2}\ln\left(\frac{z^0}{H}\right)\right\}. \tag{F28}$$

This formula should, of course, reduce to the flat terrain form simply by setting $z_T$ equal to a constant. By choosing the constant value to be the spatial average terrain height, denoted by $\overline{z}_T$, we derive the ratio formula for the maximum spotting distance in the form:

$$\int_0^{X^*} \frac{z_G - z_T}{z_G - \overline{z}_T}\;\frac{\ln\left(\phi\,\dfrac{z_G - z_T}{z_o}\right)}{\ln\left(\phi\,\dfrac{z_G - \overline{z}_T}{z_o}\right)}\,dX = X^*(\text{flat terrain}). \tag{F29}$$

The right hand side of equation (F29) is the maximum spot fire distance over flat terrain *using the windspeed (as a function of height) that obtains at the average terrain height.*

The integral in this equation can be simplified by considering only cases for which

$$|z_T - \overline{z}_T|/(z_G - \overline{z}_T) << 1; \tag{F30}$$

for these cases, since

$$(z_G - z_T)/(z_G - \overline{z}_T) = 1 + (\overline{z}_T - z_T)/(z_G - \overline{z}_T), \tag{F31}$$

$$\ln\left(\phi\,\frac{z_G - z_T}{z_o}\right) \doteq \ln\left(\phi\,\frac{z_G - \overline{z}_T}{z_o}\right) + \frac{\overline{z}_T - z_T}{z_G - \overline{z}_T} \tag{F32}$$

and so

$$X^* + \int_0^{X^*} \left(1 + 1/\ln\left(\phi \frac{z_G - \overline{z}_T}{z_o}\right)\right) \frac{\overline{z}_T - z_T}{z_G - \overline{z}_T}\, dX \doteq X^*(\text{flat terrain}). \tag{F33}$$

The variation of terrain height relative to the average height can be represented with good generality by a sinusoid,

$$z_T - \overline{z}_T = a \sin\,(m(X + X_1)) \tag{F34}$$

where

$2a$ = total elevation difference, ridge to valley

$m = \pi \div$ horizontal distance from ridge to valley

$X_1$ = horizontal location of firebrand source
($X_1 = 0$ is midslope on windward side of ridge).

This form leads to a transcendental equation for the maximum horizontal distance:

$$X^* + \frac{(1 + \alpha)a}{m(z_G - \overline{z}_T)} \left\{\cos\,(m(X^* + X_1)) - \cos\,(mX_1)\right\} = X^*(\text{flat terrain}) \tag{F35}$$

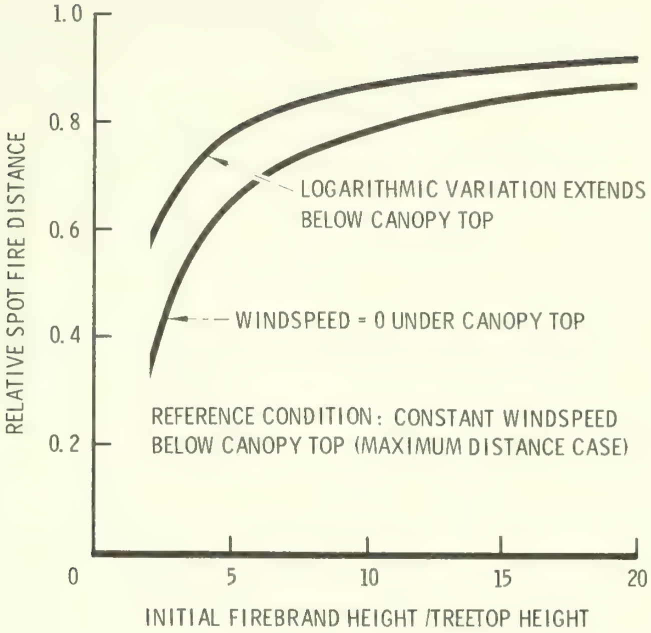
where

$$\alpha = 1/\ln(\phi(z_G - \overline{z}_T)/z_o). \tag{F36}$$

Equation (F35) was solved for the ratio of maximum distances and plotted in the text. The four cases presented in the text correspond to different values of $mX_1$. The values used are as follows:

| $mX_1$ | *Location of firebrand source* |
|---|---|
| $\pi$ | midslope on lee side of ridge |
| $-\pi/2$ | valley bottom |
| 0 | midslope on windward side of ridge |
| $\pi$ | ridgetop |

For the numerical results plotted in the text, the value of $\alpha$ was set to 0.2 and $z_G - \overline{z}_T$ to 6,000 ft. These values, along with $\phi = 0.12$ (see appendix E), imply a roughness scale of $z_o = 4.9$ ft. The weak dependence of the resulting ratio of maximum ranges on the parameter a implies that the numerical value of $\alpha$ is not critical in this range of values. The location of the firebrand source is very important, however.



*Fiure F-1.--Effect of different indspeed profiles on pre- icted maximum spot fire istance.*

*Brning Rate Model Influence*

Note that if the firebrand burning rate were different from the model used hre (i.e., if a different value of the burning rate regression parameter b of apendix C were used) only the value of $\tau$ would be changed. The scaling relationsips would be preserved between flat terrain and uneven terrain results. The ipact of a change in the burning rate would be to change the numerical coefficent K in equation (F9) and hence the value of the coefficient in equation (F22). Te number 21.9 in the latter equation is inversely proportional to the square rot of the burning rate coefficient K, so results for spot fire distance should b altered accordingly to reflect a different K value.

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ALBINI, F. A.
1979 Spot fire distance from burning trees--a predictive model
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and Range Exp. Stn., Ogden, Utah

Presents a predictive model for calculating the maximum spot fire distance expected when firebrands are thrown into the air by the burning of tree crowns. Variables included are: quantity and surface/volume ratio of foliage in the burning tree(s), height of the tree(s), and the wind field that transports the firebrands, and the firebrand burning rate. No validation data are available at present.

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USDA
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INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION
FOREST SERVICE
U.S. DEPARTMENT OF AGRICULTURE

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# A GUIDE TO RECLAIMING SMALL TAILINGS PONDS AND DUMPS

Gerald Harwood

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

# RESEARCH SUMMARY

This report presents a sequential approach to reclaiming small tailings ponds and dumps in the Western United States. The report is based on a SEAM-funded project on the Sheldon Mine, an abandoned copper operation near Prescott, Ariz. The information herein is intended to aid land managers and reclamation specialists in planning and implementing reclamation of small tailings ponds and dumps.

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# Chapter One

# INTRODUCTION

According to a 1966 estimate by the U.S. Breau of Mines, more than 16,000 inactive ad/or abandoned underground mines are scatted throughout the Western United States. Mre recent estimates have suggested that this li is incomplete and that the actual count may bmore than twice as high. For instance, Colorao, alone, has more than 10,000 abandoned pospect sites. Many of these sites create contiuing environmental damage in the forms of acd drainage into streams, lakes, and undergrund water supplies; production of sediment tht shortens the life of lakes and ponds; and, vial disruption of scenic landscapes. Further, thse abandoned mines that are still open to the suface pose a potential danger to anyone who wuld explore them.

In recent years, Federal and State agencies hae been increasingly interested in the reclamaton of these orphaned mines. However, historcly this interest is a new phenomenon. Therefoe, relatively little is written on the subject. Ts guide attempts to partially fill this void hough discussion of problems and practices ht may be encountered in the reclamation of abndoned underground mines. The approach taen is largely a qualitative one because, as yet, thre are few hard rules and facts that specifically aply to such projects.

When first considered, the prospect of urlertaking the reclamation of a small mine site my appear to be deceptively simple. In truth, suh tasks can become highly complex. What my initially appear to be a simple matter of regrding and planting, occasionally can have the potential for generating a tangle of ecological, egl, and/or political problems. In addition, it is pssible that the selected treatment simply may nc be adequate to correct the conditions that exit at a given site. Accordingly, this book has ben designed to lead planners, land managers, an contractors through various technical, enviinmental, economic, soical, and political aspets of planning the reclamation of orphaned me sites by providing a basic background for the kinds of problems and situations that may be encountered. It is not designed to replace technical or legal consultants, whose services can often be invaluable in various phases of a project.

Because abandoned mines involve extremely diverse circumstances, the scope of this guide is as broad as possible. Its primary intention is to raise questions and discuss relationships, rather than to provide specific answers to problems that can only be determined individually for each project site. Some chapters are included to assist in the analysis of problems and gathering of data, while others assist with the actual planning of the reclamation operations and post-project maintenance and monitoring. The author assumes that a cost-benefit analysis has been completed before commencement of the serious project planning; therefore, this topic is not considered.

For the convenience of the reader, a question and answer format is used in portions of this book. Questions and points of wide applicability are raised, then discussed in general terms. However, certain items are not discussed further, because it is felt that their mention, alone, would be sufficient to initiate consideration by the reader. Also, it should be emphasized that many of the questions raised have no single or simple "correct" answers. Each situation encountered in the planning of a reclamation project must be dealt with in the context of those conditions unique to a particular mine site.

In addition, technical terminology is kept to a minimum. Many of the terms that are used are defined in the text, while others are included in the glossary in the appendix.

This handbook was conceived in connection with the reclamation of the Sheldon Mine tailings pond and waste dump at Lynx Creek, located near Prescott, Arizona. The project was a joint effort by Surface Environment And Mining (SEAM), the Prescott National Forest, and the University of Arizona. Because of the difficulties encountered during the reclamation of the Sheldon Mine site, it was decided that there was a need for a project planning handbook. These experiences are used to illustrate various points in this guide. For this reason, brief summaries of the history of the mine, the ecological problems it generated, and its reclamation are include Although this guide is partially based upon specific project, it is hoped that it will prove be generally applicable to a wide range abandoned mine sites located throughout t Western United States.

# The Lynx Creek Experience:

# An Account of a Pilot Reclamation Project

Probably, the history of the Sheldon Mine is typical. It is briefly reviewed here to illustrate the evolution of a mine site over several generations of operation. Mining and processing techniques change with passing time, as do the economic conditions that ultimately control the development of a mine and the possibility of reworking its tailings. As discussed later, the operational history of a mine directly affects the structure and content of its waste dumps and tailings ponds.

## THE SHELDON MINE

The Sheldon Mine is located within the Lynx Creek watershed in the Prescott National Forest, approximately 12.8 km (8 miles) southeast of Prescott, Arizona. This area had been the site of considerable gold and silver mining activity, which sporadically continued for nearly a century following the discovery of gold in 1863. In addition to numerous underground mines, Lynx Creek itself was placer mined from the late 1880's until World War II.

The town of Walker, Arizona, grew up in the midst of numerous mining claims along Lynx Creek. In 1863, Captain Joseph Walker, led a mining expedition into the Hassayampa Creek area of the Arizona Territory. Their prospecting activities eventually led to the adjacent Lynx Creek watershed, where they found veins of gold, copper, silver, and lead. With the establishment of the town of Walker as the first Anglo-Saxon community in northern Arizona, the population grew until it reached its peak of 3,000. For a while this was the largest settleme in Arizona. The town experienced several pop lation fluctuations that paralleled mining act ities in the watershed. In the 1930's, it rapic declined. Then, after a brief flurry of mini during the early part of World War II, it gradua disintegrated. Today, there are several acti mining claims and summer cabins in the distri along with some permanent residents.

Gold was found at the site of the Sheld Mine in December, 1882. Almost 17 years late in 1899, a patent was filed. The deposit was p riodically worked under various owners, fro the turn of the century into the 1950's. Produ tion on the Sheldon, which became one of th largest mines in the Lynx Creek watershe peaked in the 1920's when its shafts had reach the 92-m (300-foot) level. Mixed ores from th mine were carried by rail from Walker, through tunnel under a mountain, to the mill at Pola Junction. During this period, dewatering (remo ing water) became prohibitively expensive, so decision was made to rework the tailings. Th involved regrinding the tailings, then, through flotation process, separating out the residu heavy metals. The slurry containing the fin residue was then transported in a wooden pip line to the present Sheldon Mine tailings pon where it was dumped. By 1936, copper, lea gold, and silver, then valued at a total $1,075,000, had been removed from the min In the 1950's, the mine was reactivated, wi workings extended to the 183-m (600-foot) leve The operation, however, was eventually aba doned as the cost of dewatering again becam prohibitively high. The buildings at the site we

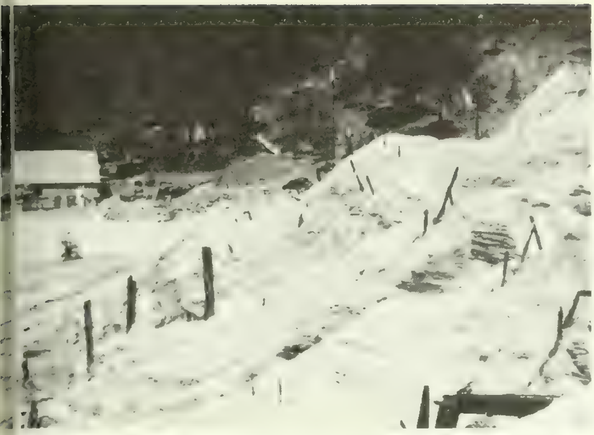


Fig. 1 **The Sheldon Mine tailings pond produced severe erosion.**

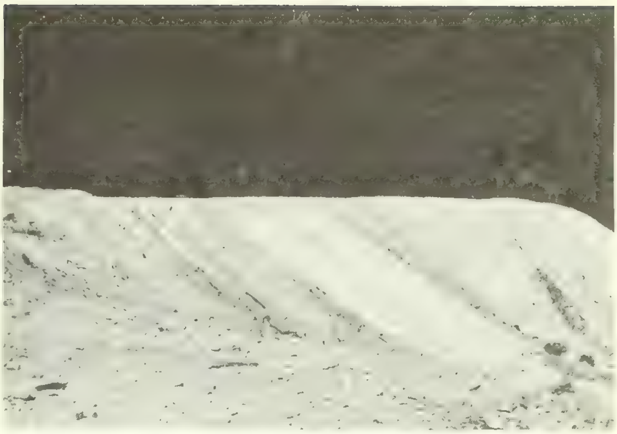


Fig. 2 **The Sheldon Mine dump covered approximately 1.8 ha (4.6 acres).**

eventually removed and the main shaft was plugged and covered over, leaving only a large dump and tailings pond covering approximately 1.6 ha (4.6 acres) and 1.42 ha (3.5 acres), respectively (figs. 1, 2).

# ECOLOGY OF THE LYNX CREEK WATERSHED

## General Description

The Lynx Creek watershed covers an area of approximately 7300 ha (18,038 acres) and is located in a semiarid region having a mean annual precipitation of 47.42 cm (18.67 inches). Usually, most of the precipitation occurs in late summer in the form of localized afternoon thundershowers. Milder and more generalized storms occur in the winter, with nearly half of the precipitation in the form of snow, which may accumulate to a depth of 1 m (3.3 feet). At other times of the year, precipitation is rare. Consequently, flow in Lynx Creek is greatest during periods of spring snow melt and summer rains. Its annual stream flow varies from 500 000 to 2.5 million cm (132 to 660 million gallons) of water, with an average estimated at approximately 700 000 cm (185 million gallons) per year. Finally, the elevation at the Sheldon Mine is approximately 2 12 m (6,600 feet).

Within the watershed, the soils are predominantly granite and schist in origin, and the slopes range from 30 to 60 percent. Generally, the soils tend to be shallow and contain considerable amounts of gravel with a texture of loam to silt loam. Also common are areas with stones and rock outcropings. Finally, the dominant vegetation type is ponderosa pine associated with several species of oak, mountain mahogany, and black walnut. Several species of grass are also present.

## The Ecological Problems of Lynx Lake

In 1963, the Arizona Game and Fish Department constructed a dam on Lynx Creek approximately 16 km (10 miles) southeast of Prescott, creating Lynx Lake (fig. 3). A campground was constructed near the 22.26-ha (55-acre) lake, which was primarily intended to be a recreational facility offering cold-water trout fishing. Unfortunately, the water quality of Lynx Creek was not tested before construction of the dam. Eventually, it was discovered that populations of cold-water trout cannot be permanently established in the lake. It is thought that this is due to the presence of sediments, which make the lake water toxic to many algal species and other organisms in the food chain of the trout.

A rather high rate of erosion in the watershed results in an annual flow of about 2 900 cm (102,000 cubic feet) of sediment into the lake. Most of this sedimentation occurs during periods of peak flow in the creek. Preliminary studies by the Arizona Bureau of Mines, the Arizona State

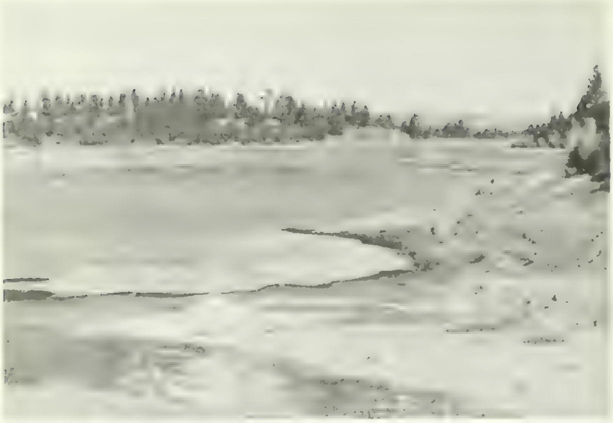


Fig. 3 **Lynx Lake was the recipient of erosion from the tailings pond and mine dump.**

Department of Health, and the State Game and Fish Commission identified the presence of high levels of manganese, copper, cyanide, arsenic, zinc, and sulfate in the sediments. Further, drainage from the Sheldon Mine and its tailings was indicated as a probable major source of these toxic substances.

# RECLAMATION OF THE SHELDON MINE DUMP AND TAILINGS POND

## Treatment Objective

The primary objective of the reclamation project concerned improving the aquatic balance of Lynx Lake through reduction of the flow of sediment and toxic materials in Lynx Creek, and improving the esthetic quality of the watershed.

## Analysis of the Tailings

A preliminary examination of the watershed indicated the presence of numerous surface disturbances and drainage from underground mines that have the potential to contribute toxic materials to Lynx Lake. These disturbances include numerous prospects and small mines with tailings ponds, waste dumps, and shafts. Also present are exposed ore-bearing formations, private roads, residences, and grazing areas that collectively contribute toxic runoff to Lynx Creek. However, the largest disturbed areas within the Lynx Creek watershed were the Sheldon waste dump a tailings pond.

Analysis of samples from the Sheldon wa dump and tailings pond indicated that they c sisted largely of quartz, feldspar, pyrite, serici and limonite, as well as high concentrations heavy metals. The samples were highly acidic. addition, analysis of water leached from t waste dump, from a lateral working beneath and from the tailings pond showed that it c tained high concentrations of soluble salts copper, lead, zinc, iron, and sulfur. Finally t bed of Lynx Creek, between the Sheldon Mi and Lynx Lake was also laden with toxic se ment. This information, combined with the fa that the Sheldon is the largest abandoned mi in the Lynx Creek watershed, indicated that i was probably the major source of the ecologi problems of Lynx Lake.

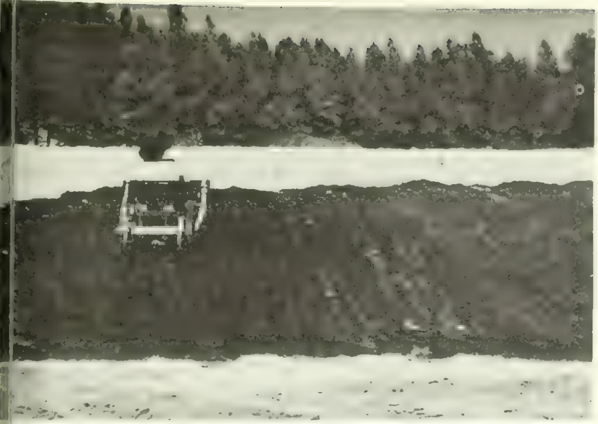
## Approach to the Problem

While the preliminary analysis indicat many sources of toxic chemicals in Lynx Cre it was not economically possible to treat th all. The highest priority was given to the tre ment and reclamation of the Sheldon wa dump and tailings pond. While the proj focused on treatment of the Sheldon Mine si it was acknowledged that a complete solution the problems of Lynx Lake would probably quire eventual treatment of many additional si and the sealing of at least one lateral worki that drains into the creek from beneath t Sheldon waste dump.

Various treatments were selected th would serve to improve the quality of water Lynx Creek and the appearance of the proje site. These include surface recontouring, deto fication of surface tailings and waste-dump m terial, control of drainage from the dump a pond, diversion of offsite water around t dump and tailings pond, and revegetation of t site through seeding and planting.

## Treatments

**Dewatering.** The first treatment underta at the site included draining the standing surfa



**g. 4 Topsoil was applied to the tailings pond at a thickness of .15 cm (6 inches).**

d subsurface water from the tailings pond by enching. This was done several months in ad- nce of subsequent treatments to make the pond rface workable with heavy equipment.

**Recontouring.** Recontouring the pond and ump is designed to modify or eliminate irregu- rities of shape, create more gentle and stable opes, retain moisture that falls on the site, and event or control runoff from adjacent ground nto the treated sites. To accomplish this, exist- g erosion gullies were filled in and compacted. general, recontouring is designed to blend sually with the surrounding landforms.

**Soils and amendments.** To neutralize the urface acidity of the tailings, a layer of limestone pproximately 75 000 kg/ha) was applied to he entire tailings area, then overlaid with 30 cm foot) of alluvial topsoil. Then the topsoil was ompacted to a thickness of about 15 cm (6 nches) (fig. 4).

**Revegetation.** The primary intent of revege- ation is to reduce surface runoff. In this case, a ixture of grasses and legumes was selected, be- ause the subsurface conditions were deemed nsuitable for the growth of trees, and it was de- irable to establish a permanent organic soil layer s rapidly as possible. Approximately 18 kg/ha 16 lb/acre) of seed were used. The seeds were ither broadcast or mixed with a hydromulch omposed of water, wood fiber, and a petroleum- ased emulsion. This emulsion is used to stabilize he material against wind dispersion. Then, the rip irrigation system was installed.

**Drainage control.** Diversion channels are constructed to shunt offsite drainage around the treatment areas. Onsite water flow is controlled by terracing of the steeper slopes into smaller runoff areas and impounding the water in swales, which dissect the slope.

**Esthetic consideration.** Surface recontouring is designed to conform to the surrounding natural landscape. In this case, a protective fence was constructed of rails so that it blended with the rustic setting.

## Early Effects of Treatment

After 1 year, the physical appearance of the tailings was greatly improved. Good grass cover was present and naturally seeded trees were becoming established. Two followup lime treatments have been required and maintenance of peripheral drainage channels has been necessary.

## WHAT WAS LEARNED FROM THE LYNX CREEK PROJECT?

This section discusses a variety of specific problems that arose in connection with the project. Also included are other observations that may be of value to those attempting similar reclamation projects.

## LIME APPLICATION

Supplemental lime applications were required at the site, indicating the need for careful planning concerning the amount and quality of the lime that is used. Traditional agricultural rules concerning the amount of lime to be applied per hectare (acre) do not necessarily apply to highly acidic waste materials. It is suggested that site-specific analysis of the waste materials be made and that the quality and quantity of lime required be experimentally determined. Further, the method of lime application is important. For example, in this situation, surface application is not highly effective. The possibility of placing lime in pits or auger holes distributed at intervals might be investigated as a means of treating waste materials to a depth of several meters (feet).

## TAILINGS POND DEWATERING

While the Sheldon pond was drained several months in advance, difficulties were still encountered in the course of subsequent treatment with heavy equipment. This indicates that care should be taken to remove the water from the pond far enough in advance to allow for settling and for the surface to become workable. It may be necessary to dewater at least 1 year before subsequent treatment.

## TOPSOIL SELECTION

Topsoil needs to be selected for texture, available water holding capacity, organic content, and spreadability. For instance, silty loam would be superior to alluvial soil having low clay content. Also, the presence of rocks of moderate size, up to 0.3 m (1 foot) in diameter, can be of value. This is because they can be "walked" in with a caterpillar and will serve to both anchor the soil and provide small areas of disturbance that will foster the development of plant cover. Finally, the depth of applied topsoil must be adequate to support full development of the root structures of the planned vegetative cover species.

## SLOPE ABUTMENTS

At Sheldon, it was found that gabion structures are highly effective and durable, both as retaining devices and to protect water channel banks at locations subject to serve water forces.

## SEEDING

Hydroseeding with petroleum-based fiber mulch proved to be well suited for use on surfaces of the treated waste dump and tailings pond (fig. 5). The mulch has adhesive properties that protect the fibers from wind and water erosion. Attempts were made to establish tree seedlings, but the topsoil layer was not deep enough to support them or to protect their roots from chemicals contained within the waste materials below. Therefore, it is recommended that tree seedlings be planted in pits, of a depth and diameter of about 1.2 m (4 feet), that have been given an adequate protective layer of lime and the filled in with topsoil. This should provide a goo substrate for the trees, until they have reached moderate size.

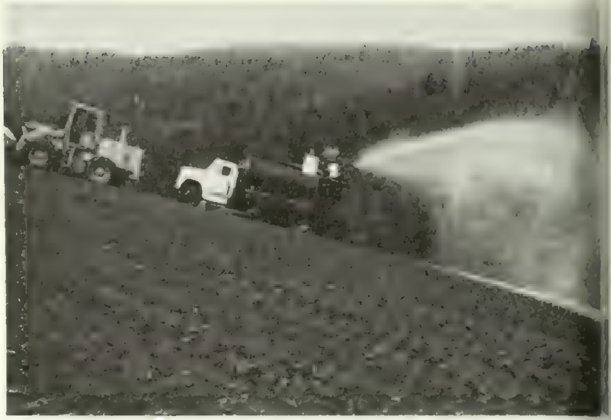


**Fig. 5 Hydroseeding operation on the mine dump.**

## IRRIGATION SYSTEM

The drip irrigation system that was installe at the site proved to be economically impractica to maintain. This aspect should be considered i the design of such systems.

## SITE PROTECTION

Disruption of the site by grazing animal and motorcyclists indicated the need for protec tive fencing. Heavy fence rails have been foun to be more effective, esthetically pleasing, an durable, than small ones.

## PRELIMINARY SITE EVALUATION

Careful preliminary evaluation of a sit should be made, particularly with respect to th magnitude of the treatment that will be required At this time, all aspects of the site's problem should be identified, and adequate funding se aside for their effective treatment. Incomplet treatment or undertreatment can seriously under mine the overall effectiveness of a project an result in the need for costly supplemental treat ments.

# Chapter Two

# PLANNING THE RECLAMATION PROJECT

## Introduction

One of the first tasks in planning a reclamaton project is to determine the magnitude and etent of the impact of the disturbance to be tated. In beginning the planning phase, it will b important to identify the original ecological poblems that made the project necessary, as vell as anticipate project related problems that right occur in the course of the reclamation pogram. Careful analysis of problems in the panning phase should serve to minimize additonal difficulties once the project is underway.

The planners will need to accurately ascertn the size and boundaries of the abandoned se and the extent of offsite lands that are ecolgically disturbed by it. Also, it will be necessry to identify as many aspects of the ecological csturbance as possible. Then, specific objectives t be accomplished by the project treatment pogram should be devised. Usually, these objectves will be used to reestablish a harmonious reltionship between the abandoned mine site and te remainder of the ecosystem of which it is a prt. Also, the objectives will need to incorporate te planned future use of the land. Determining te future use of the abandoned mine site can be he of the most important aspects of the planng phase of a reclamation project, because it an significantly affect various phases of the eatment such as the final shape of the reconoured land and the selection of vegetative cover. he assessment process will require the gathering nd evaluation of a variety of data for use in the lanning process and, later, in the selection of pecific treatment methods.

It is very important that the planner be aware of the fact that there may be important ocial, political, and economic aspects to the original ecological problems and their remedies. For this reason, questions of past, present, and future land use; ownership; and jurisdiction assume an importance nearly equal to that of ecological considerations in the planning process.

This chapter raises certain key questions that confront the planner in the formulation of a mined land reclamation program. Due to the individual nature of each abandoned mine site, these questions must be discussed in generalities, because specific answers can only be ascertained by the planners for their specific project application. Undoubtedly, the questions raised here will only be harbingers of many specific and sometimes difficult questions that will be encountered in the course of planning a reclamation project. Primarily, this chapter is concerned with developing an overall grasp of a project through the identification of existing and potential problems, data gathering and analysis, and project objective outlining. Following is an attempt to list some of the more important problems that may be encountered by project planners. Like the questions, specific problems will vary from site to site. The selection and planning of specific site treatment methods will be considered in Chapter 3.

Numerous situations will arise in both the planning and operational phases of a project where expert advice will be invaluable. Judicious use of expert technical and legal advice can result in significant savings of both time and money. In some situations, it may make the difference between the ultimate success or failure of a reclamation project.

### WHAT ARE THE BOUNDARY CONDITIONS OF THE DISTURBED SITE AND THE AFFECTED ECOSYSTEM?

In planning a reclamation project, it is essential to be certain of the legal, physical, and ecological boundary conditions of the abandoned mine site and adjacent or downstream lands that are affected by it. Legal boundaries will affect ownership and jurisdictional questions that may arise in connection with the project. The physical boundaries of the site, and the extent of the ecological disruption produced by it, will determine the extent of the area to be treated. The latter information will also aid in the identification of other sources of disturbance not located on the proposed treatment site. Some of the required information may be obtained from topographical maps and records, while drill cores and land surveys may be necessary to ascertain the volume of the tailings and the physical extent of the disturbance. This knowledge is essential when estimating the magnitude of the reclamation effort to be undertaken.

Also, it is essential to recognize and understand the roles of the various component parts making up the ecological systems within the watershed and how these parts are affected by the disturbance. These components will include the terrestrial, aquatic, and atmospheric phases of the physical environment and the animate, vegetative, and microbial sectors of the biotic phase of the system to be treated. Life forms that live in the soil must also be considered.

Frequently, planners will encounter problems when they find that boundaries, whether politically or scientifically delineated, are generally arbitrary by nature. Ecosystems transcend boundaries devised by humans; therefore, so may the ecological impact of abandoned mine tailings. For this reason, project planners may have to arrange for treatment programs that cross jurisdictional boundaries and property lines and, even in cases where this is not feasible, it should be recognized that the impact of the treatment may transcend such lines. Related to this problem is the fact that jurisdictional matters may also prohibit the elimination of environmental problem sources located upstream from the mining site in the watershed, even though they directly affect the abandoned mine site and contribute to the problem ascribed to it. In such cases, alternative solutions may have to be found.

## WHAT KINDS OF PROBLEMS HAVE BEEN PRODUCED BY PAST MINING ACTIVITIES?

One of the major tasks that must be addressed in the planning of a disturbed area's reclamation is the accurate identification of th exact nature of the problems that have resulte from the land disturbance. A good first step is prepare a detailed list of all of the problems th have been attributed to the disturbance and order them into useful categories. The specif categories selected may vary from site to sit but they might include water quality, soils, veg tation, and land use. Most of the problems pr duced by an untreated site can be separated in two major classes: (1) those that affect enviro ment; and (2) those that directly affect peopl Although there will be some overlap, this distin tion can be an important one, because it may b come necessary to "sell" a project to landowne In such a situation, it will be valuable to be ab to show people how the ecological problems the site adversely affect them with regard such practical considerations as land use, proper values, and taxation.

## Environmental Problems

In the course of problem analysis, it is ir portant to determine whether each listed item an effect of the disturbance caused by the aba doned mine, or derives from some other sourc For example, if a lake or stream cannot suppo a population of fish, the source of the polluti could be local sewage, rather than contaminati of the water by chemicals from an abandon mine. Such questions can often be resolved on with the aid of field or laboratory analyses. Tl following list suggests some possible enviro mental problem areas:

- Reduction of surface and/or grou water quality by toxic chemicals fro tailings ponds and waste dumps that m adversely affect animal and/or vegetati life.
- Reduction of air quality by dust fro the abandoned site where vegetation ca not grow.
- Alteration of the microclimate due large land areas devoid of significa vegetative cover.
- Destruction of onsite and downstrea animal habitats by such things as mu

flows, sedimentation, and chemical leaching.

- Erosion and related problems, such as destruction of soil surfaces, destructive alteration of the landscape, and silting of water bodies downstream in the watershed.
- Physical and vegetative disruption that results in reduction of the esthetic quality of the disturbed site and the creation of visual disturbances that are detrimental to land elsewhere in the watershed.

## ocial, Political, and Economic roblems

In the planning of a technological project, is often easy to lose sight of people-oriented roblems. This class of problems has two comonents that importantly relate to reclamation rojects: (1) problems, which are generated by he site, that affect people; and (2) problems, vhich are generated by people, that will directly ffect the project. In the first category, esthetic nd ecological disturbances produced by the site an adversely affect property values and land-use otentials elsewhere in the watershed. This is articularly true when water quality is affected o preclude its domestic, agricultural, or recreaional use. These affected property values will in urn affect both regional prosperity and the tax ase. At this level, the problems generated by he site may take on political connotations. The econd category of potential people involvement n a reclamation project is discussed later.

## S THE PROPOSED USE FOR THE RECLAIMED LAND SUITED TO THAT SITE?

Before this question can be properly addressed, various factors involved in the determination of possible uses for the land must be considered. These factors include the physical, chemical, and biological limitations of the land, as well as socioeconomic demands and prohibitions. For example, it is possible that ore-bearing outcrops and/or mines elsewhere in the affected watershed may contribute toxic materials to downstream sites. For a variety of ecological, legal, or social reasons, it may not always be possible to correct these situations. Therefore, land-use plans for the site to be reclaimed may have to be altered. The following is a list of items that will need to be considered in this context:

- Toxic chemicals may be present in the waste materials and may permanently limit the potential vegetative growth or possible uses of the disturbed site.
- Site-imposed biological limitations can restrict the eventual development of vegetation or animal life on the site. For example, the potential for vegetative climax on the site may not be equivalent to that on adjacent land.
- Possible adverse environmental affects of the proposed uses of the land need to be considered, such as: Will the proposed land use significantly increase auto traffic? Will it increase human population density and place a strain on water supplies and sewage disposal? Will pressures for commercial or residential development and utility installations be increased?
- Are there physical limitations to the possible uses of the site that are imposed by surface contours or obstacles?
- Are there political or legal restrictions that may limit possible uses for the land? Is the land under public or private ownership? Are there specific zone or unit plans or restrictions?
- Are there limiting social or economic factors that will affect the possible uses of the land? The value of the land will economically determine, in part, its relative suitability for agricultural, recreational, or alternative uses that offer greater economic return.
- Does the land offer a high natural potential for some particular use such as recreation? Related considerations include ease of access to a site and its proximity to human centers, special features such as bodies of water or usual scenic or historical interest, and existing vegetation that

might offer potential camping or picnicking sites.

A key question is whether or not a treatment program will be able to overcome physical, biological, and/or chemical limitations such as those listed above. A variety of options may exist for possible use of a site, including recreation, agriculture, residential, commercial, or possibly no specified use at all. Some reclamation projects may be undertaken for the protection of adjacent or downstream land or for esthetic improvement of adjacent land, rather than by way of interest in the primary mine site itself. The possible options and the use selected will be different for each treatment site, and the decision made will affect the objectives of the reclamation project. Where possible, it will be desirable to include input from local area inhabitants in making the final land-use determination.

## WHAT ARE THE OBJECTIVES OF THE PROPOSED RECLAMATION PROJECT?

After ascertaining the ecological problems associated with the site and deciding on a prospective use for the reclaimed land, specific reclamation objectives should be outlined. While the particular set of objectives prepared for a given project will depend on the individual situation, certain general criteria need to be considered in their formulation. For instance, the objectives should be both logistically and financially feasible, while meeting with general public acceptance. Also, they must be acceptable to those responsible for the management of the disturbed land and the affected watershed. In addition, the project should be aimed at producing environmentally sound and stable conditions that will ultimately reintegrate the disturbed area into the general ecosystem, while alleviating as many of the initially perceived problems as possible. Minimally, the project objectives need to bring the site into compliance with applicable Federal, State, and local environmental quality regulations and existing legal and safety standards.

## WHAT KINDS OF INFORMATION AND DATA NEED TO BE COLLECTED IN THE PLANNING OF A RECLAMATION PROJECT?

The majority of data required for plannin a successful project may be categorized as: e vironmental; historical, with respect to minin operations and other past land uses of the sit and social, economic, and political factors th may relate to the reclamation of the site.

The data gathered will be useful in form lating realistic objectives for the reclamati project and/or tne assessment of alternative la uses. For example, water analysis data will in cate those kinds of treatment that will be nec sary to improve water quality. Plant invento data from the ecosystem surrounding the d turbed area will suggest the best species to rei troduce to the disturbed land. Hydrological a meteorological data will aid in determining t necessity of recontouring the disturbed are Sociological data will help to ascertain the ne essity for, and best approach to, public relatio work before implementing the planned project

Once the treatment of the site is underwa the collected data will assist in assessing t progress of the project and evaluating its ultima success or failure, long after completion.

## WHAT TYPES OF ENVIRONMENTAL DATA WILL BE NEEDED?

In addition to listing the perceived proble of the ecosystem or watershed affected by t disturbed land, and those of the disturbed site self, it will be necessary to conduct various s veys and analyses to establish baseline or "n mal" levels for the different components of ad cent, undisturbed portions of the ecosystem. T data can be compared with information tak from the disturbed site before, during, and aft the treatment program. The specific kinds data that should be gathered will vary with t particular site and might include, but not limited to, the following items:

- Land and hydrological surveys of the d turbed site are important in determini its precise relationship to the remainder of the watershed. Hydrologic data aid in determining the necessary treatment methods, and assessing the potential for contamination of water supplies elsewhere in the watershed. Also, a survey of the site should be made to ascertain potential hazards above and below the surface resulting from past mining activities and from such natural phenomena as landslides, snow avalanches, mudslides, and flooding.

- A drainage map is useful in several ways including planning of drainage from the site and protection of the site from erosion. Also, the map is useful in locating possible sources and/or concentrations of contaminating materials derived from the site to be treated, or other locations in the watershed. Finally, the map should note the location of roads, other mines, mineralized outcrops, construction sites, buildings, and grazing patterns in the watershed. These items offer potential for erosion and the introduction of sediment and/or toxic chemicals into the drainage system of the watershed.
- Meterological data are valuable in planning recontouring of the land surface, revegetation methods, and species selection. This information aids in predicting flood and erosion potential and determining possible need for establishing microhabitats to assist revegetation and repopulation of the site.
- Water quality data provide information for the planning of treatment methods to bring about compliance with environmental standards.
- A mineral analysis of tailings from the pond and waste dump, including core samples to ascertain the extent and chemical composition of tailings and their potential for contaminating surface plants and water supplies, is essential for intelligent planning of reclamation treatments. This information can be an important factor in planning movement of waste materials in the recontouring process. It is important to note that the chemical content of the tailings may significantly differ with respect to depth and horizontal position in a given pond or dump.
- A vegetation analysis is needed to compare the disturbed site with adjacent land in the ecosystem. Obtain species lists and note plant distribution and density. These data should be considered along with meteorological and other abiotic environmental data in determining the vegetational climax potential of the disturbed site.
- Obtain wildlife data from the surrounding adjacent land. Then combine this information with data concerning food chains on the adjacent land to ascertain the potential zoological population composition and density for the reclaimed disturbed site. This information is also valuable when planning possible surface restructuring so as to provide niches for certain species.
- A visual analysis of the disturbed site and its surroundings is an important aid in planning esthetic improvements. The visual analysis should include such data as the locations of points in the surrounding area from which the mine is visible and the scenic quality of the surrounding landscape.
- Photographic surveys aid many aspects of data gathering, project planning, and postproject monitoring and evaluation. These surveys should be made before, during, and after treatment of the site. It is important to establish specific camera sites that can be used for subsequent photography of identical views. Also, it may be useful to document the project with motion pictures and/or video tapes.

## WHAT HISTORICAL INFORMATION CONCERNING PAST MINING OPERATIONS AND LAND USE WILL BE OF VALUE?

Information of a technical nature regarding past mining operations on the reclamation project site can be valuable both from the standpoint of project safety and its ultimate success. This kind of information might include surface and/or underground maps showing shaft locations. Two examples of this point were experienced in connection with the Sheldon Mine reclamation project. In one instance, a large and deep vertical shaft, which had been superficially covered, was accidentally discovered by a heavy equipment operator. Potentially this was a dangerous situation. The other example is provided by the presence of a lateral working located beneath the waste dump which, for significant periods after rainfall, drains chemical-laden water into Lynx Creek. If detailed maps showing the locations of the workings are available, the water might be diverted before it enters the mine.

Technical details of past mining activities on a given site may be difficult to locate, and there is no guarantee that such information even exists. But the potential benefits to be gained from such information will make the effort worthwhile.

## WHERE CAN INFORMATION ABOUT THE WORKING HISTORY AND STRUCTURE OF A MINE BE LOCATED?

If any former operators of the site are still in existence, historical information may be relatively easy to obtain. In many instances, however, the company or companies will no longer exist and operations records may have been destroyed, lost, or may have come into the possession of an executive, engineer, geologist, or their families. Sometimes, such records find their way into archives, libraries, or other repositories. The search for this kind of information may require considerable time and effort. Often, reference librarians and archivists are willing to offer their expertise in helping with the search. The following list suggests a few types of agencies that may have files containing historical information and maps. The exact names and kinds of agencies will vary from state to state (the examples given here pertain to Arizona):

- Mine bureaus and departments of mineral resources: These agencies may be State or Federal. Some may have detailed records of many large and small minin operations. Sometimes, these record may include maps of workings and the locations. In Arizona, such records ar maintained by the Department of Miner Resources in Phoenix, and microfilr copies of a portion of these files may b found in Tucson at the Bureau of Mine

- State mine inspectors: In Arizona, Stat law requires all mine operators to mak detailed operation maps and informatio available to the Mine Inspector on r quest. Such materials, however, are n kept on file by that office. Laws concern ing what must be filed with mine inspe tor offices will vary from state to state.

- State archives: State archives are usuall maintained in State capitols. They ma contain detailed maps of certain minin areas and sites. In Arizona, the State a chive collection contains shaft schemati for approximately 100 mines, both larg and small.

- State corporation commissions: Agenci governing corporations will usually mai tain files of articles of incorporation, i cluding the names of the incorporato and dates of incorporation and dissol tion. This information may be of valu in locating such persons or their familie

- Libraries, museums, and historical s cieties: Public and university librari museums, and State or local historic societies often maintain special colle tions including maps, photographs, pe sonal papers, and newspapers. These m contain detailed information about mi ing districts and individual mines. Sta members of such agencies are invariab helpful in searching for such informatio

- National archives — Territorial record In some cases, a particular mining ope tion may have been carried out in ter torial days prior to statehood. Certa States maintain territorial records th predate the kinds of State agencies list above. In other cases, such informati may be kept by the Federal governme in regional depositories of the Natior

Archives. These are located in Laguna Nigel, California (records for Arizona, southern California, and Clark County, Nevada); Denver (records for Colorado, Montana, Utah, and Wyoming); Fort Worth (records for New Mexico); San Francisco (records for northern California and Nevada); and Seattle (records for Alaska, Idaho, Oregon, and Washington).

It should be remembered that even if de-taed workings location information is found fc a given site, such records may be out of date. F this reason, safety precautions should always observed.

## S cial, Economic, and Political Data

Earlier in this chapter a distinction was nde between the effects of an abandoned mine i and its reclamation on people and the ways n which people can affect a reclamation project. 3ch of these may be considered people-oriented blems, which must be addressed by reclama-i n project planners.

For this reason, a program of public rela-i ns and involvement of the public in planning elamation projects can be beneficial. Public osition to a project could conceivably come m several directions. For example, owners of ghboring land might object to the reclamation a site by reason of feared potential damage to ir land, an increase in the tax base of their d, or objections to the proposed use for the laimed site. Such objections must be met by nners with diplomacy and from a position of tual knowledge about the real benefits and blems to be derived from the reclamation of ite.

In this regard, an essential question to be dressed by the planner is whether or not the oposed treatment will adversely affect, or be blicly perceived to adversely affect, offsite nd elsewhere in the watershed. If so, what will the actual effects and how great will be their agnitude? It is important to be aware of the ct that many of the problems encountered in anning may appear to be simple ecological atters, but may in fact be extremely sensitive om a sociopolitical point of view. The following list of topics is intended as a guide for consideration by the planner. It is not all-inclusive, however, because various other matters may arise as the planning of a project progresses.

**Legal matters** (additional legal considerations are discussed in Chapter 3). Legal research is required to find out about laws regarding land use and environmental standards, such as air and water quality. This research should be done at the local, State, and Federal levels.

In addition, a variety of questions related to land ownership must be addressed. One question might be who owns or has jurisdiction over the land on which the abandoned site is located (it is important to distinguish between surface and mineral rights). Another is who owns land elsewhere in the watershed that is adjacent to or affected by the disturbed site. A third question might be is there a possible need for condemnation of the land. Finally, will there be a need for expenditure of public funds on private land, which can be a possible source of legal and political difficulties?

**Topics related to land use.** It will be necessary to define the present major uses of the disturbed site and of land elsewhere in the watershed that is affected by the site in one way or another.

Also, the land-use history of the impacted site(s) should be examined. The present land use of the site and land elsewhere in the watershed must be considered when ascertaining the future use of the site. If the project will alter traditional land-use patterns at or near the site, considerable resistance to the project may be encountered.

In addition, it will be necessary to determine the legal options for potential land use.

Finally, the following questions should be asked. Is the site easily accessible? Would easy access to the site pose a danger to life or limb? Does accessibility affect the options for future use of the site?

**Public opinion.** Public opinion and perceptions related to the project must be solicited and the information incorporated into the planning process. To do this, public opinion surveys and/or hearings may be used. Also, some concerned citizens may wish to become involved in project planning.

In addition, it is recommended that the relative importance of land-use patterns, past, present, and projected, to local residents be assessed. Find out whether there is a public "consensus" concerning the best use of the disturbed land.

Other questions you might ask include: How are the problems produced by the disturbed site (such as water quality, dust pollution, and damage to the recreational potential of the watershed) perceived? Are there specific factors related to the proposed project that may generate public opposition?

Finally, is the public aware of the benefits that will accrue from the project?

**Economic factors.** It is advisable to determine the potential economic impact of the reclamation project and its consequences.

Also, the economics and energy efficiency of possible treatment alternatives should be assessed in advance of their planning.

Finally, will reclamation of the disturbed site increase on or offsite tax values? If the answer to this question is yes, considerable resistance to the project may be encountered.

**Historical and social factors.** Historical data concerning the environmental, social, and economic impacts of any previous reclamation projects in the area should be examined.

In addition, an effort should be made to understand the cultural values of the people living in the area adjacent to the project site, particularly as these values relate to land use.

**Esthetic factors.** The following are some questions that should be asked. Is the site highly visible? Is the esthetic impact of the site important to local inhabitants? Can the esthetic impact of the abandoned mine be significantly improved by the reclamation project? Is the site visible from more than one vantage point; if so, how many points and which are most critical? Is the surrounding area noted for any unique visual features? Do people visit the area because of its visual quality? Does the area have national, regional, or local appeal? How many people see the site? What distance or distances (foreground, middleground, or background) is the site from the viewer and which are most critical? What are the strongest visual elements (form, line, color, texture) in the surrounding landscape? What i the inherent scenic quality of the surroundin landscape? What is the visual management objective or objectives for the surrounding landscape

# Chapter Three

# FIELD OPERATIONS

In writing this guide, a distinction was made tween the overall planning of a project and e planning of specific field operations necessary carry out the treatment. Generalized project anning is the subject of Chapter 2, while this apter addresses the specifics of preparation for tual work at the project site and some probms that might be encountered during the operion.

Sometimes, reclamation projects are com-ex, so the joint efforts of a number of individ-ls and organizations may be required. Partici-nts in a project might include landowners or anagers, regulatory agencies, contractors, borers, engineers, scientists, and perhaps, in-rested representatives of the public. As dis-ssed in Chapter 2, it is important to promote ood public relations.

In addition, in each phase of planning, and uring the operational phase of the project, it is portant to promote communication and co-peration between all of the parties involved. his objective can be partially met by keeping eryone concerned advised of the project's pur-oses, plans, and time schedules, and of any sub-quent alterations.

## Vhat Are the Major Steps in Planning a Successful Reclamation?

First, consider the site, its problems, and e overall treatment objectives. For those who ill be intimately involved in the planning and xecution of the operational phase of a project, miliarity with the physical site, its boundary nditions (see discussion of boundary condi-ons in Chapter 2), and the overall plans of the roject are needed. A thorough understanding of e ecological problems of the site (or offsite roblems generated by it) and how the desired sults are to be accomplished by the proposed eatment will provide a background essential to e effective planning and performance of a roject.

Second, learn about the framework of regulations and restrictions that apply to the site and within which the reclamation operation must be conducted. In this regard, operators and planners should become familiar with the regulations and standards for environmental quality and legal restrictions that must be considered in implementing the project.

## OTHER MAJOR STEPS

**Prepare operational plans.** Specific operational objectives and plans for the project should be prepared for each phase of the operation. When drafting these plans, careful consideration should be given to all alternative treatment methods with respect to effectiveness in meeting treatment objectives, environmental effects, and cost and operational efficiency.

**Contracting.** Determine whether the project can be effectively handled "inhouse," or if the services of an outside contractor are required. In the second situation, obtain the services of a contractor who is able to competently execute the treatment operations.

**Equipment needs.** Equipment requirements must be ascertained in relation to various logistic and cost-benefit factors. The equipment selected should be practical from the standpoint of transport to and operation at the site, while making the best use of available labor and materials within the framework of scheduling requirements. Also, fuel consumption efficiency must be taken into account. This will be the responsibility of the contractor who is hired.

**Scheduling operations.** It is recommended that a detailed schedule of operations be prepared that considers restrictions imposed by the climate and the physical nature of the site and also coordinates such variables as the availability of supplies, equipment, and labor. As discussed in Chapter 2, it is important to plan for the execution of certain preliminary treatments (for example, thorough draining of tailings ponds) well in advance of the major phase of other project operations.

Cost estimates. Estimates should be prepared for each phase of the project, including probable costs of viable alternative treatment methods. Remember, contingency planning is always useful.

## Site-Specific Factors Affecting Individual Operations

A number of factors specific to each site can affect one or more of the individual operations of a reclamation project. These will include: treatment objectives; ecological, legal, and esthetic considerations; possible alternative treatment methods and equipment; and operations scheduling.

### WHAT KINDS OF REGULATIONS AND QUALITY STANDARDS MIGHT APPLY TO THE RECLAMATION OF ORPHANED MINE SITES?

Reclamation projects can be subject to numerous regulations and standards imposed by many sources. It is possible to list only a few of the many kinds of restrictions that may be applicable and only a few of the many types of governmental agencies that might be concerned with their enforcement. Most regulatory questions should be dealt with in the initial project planning stages (Chapter 2). There are, however, some that directly apply to field activities in the treatment process. These will now be discussed.

### Environmental quality standards and regulation

Environmental standards apply to reclamation projects in much the same way as they do to other activities that are potentially disruptive. While the end product of reclamation may be designed to improve environmental quality, care must be taken to assure that the treatment process itself does not generate water or air pollution or otherwise adversely affect the environment. The particular standards that apply may differ widely with various situations. For example, water quality standards are generally based on planned water use, such as agricultural, industrial, or domestic.

In addition, some regulations may apply to offsite activities. For example, the removal of topsoil from a remote site for use on the reclama- project is subject to environmental protection regulations.

### Environmental analyses, reports, declarations, and statements

Environmental analyses are required on Federal, as well as other categories of public land, for seemingly minor actions up to, and including, large projects. Consequently, environmental statements are required for any action that has a significant effect upon environmental quality, whether that effect is detrimental o beneficial. For example, on Federal lands, environmental analyses are required even for suc small projects as the construction of a fence Whether or not a statement will be required fo action on nonfederal lands partly depends o such factors as ownership, the degree of potentia disturbance (both on and off the site), whethe or not there will be irreversible effects on basi resources, or whether or not there will be cumulative effects, chain reactions, or secondary effects. In addition, the uniqueness of a site, o the potential of a project for the generation o significant public interest, is also important i ascertaining the need for an environmental statement.

The determination of the depth of enviro mental analysis and the type of report require for a given project is too complex for detaile consideration in this handbook. The reader is r ferred to a guidebook written by W. F. Mee and to the book on environmental quality b the Council for Environmental Quality and th EPA (see Bibliography).

## afety and fire regulations

In many instances, fire and safety plans
ave to be filed before work on a project can be-
n. Blasting must be done by licensed individuals
nd specific warning procedures must be fol-
wed, along with posting of roads. In high-risk
re areas, there may be restrictions on certain
ctivities or the use of certain kinds of equip-
ent. Often, these matters will be taken care of
y an outside contractor; but safety and fire pre-
ention are the responsibility of each person
orking on a project site. A good source of in-
rmation concerning fire prevention regulations
nd measures is the USDA Forest Service. It is
portant for personnel working on the project
be advised of fire regulations and plans.

## aintenance plans

In the initial economic analysis, mainte-
ance cost and feasibility must be considered for
ach project. Detailed postreclamation mainte-
ance plans may be required for some sites.
ven if not required, it is a good practice to pre-
are such plans for each project site.

## nformation sources for standards nd regulations

The numerous regulations and standards
hat may apply to a reclamation project are de-
ved from many sources. Also, various Federal,
tate, and local agencies may be involved in en-
orcement, and may be in a position to provide
formation and interpretive assistance. In addi-
on, ownership of the land greatly affects the
egulations to which it is subject. At the Federal
evel, such agencies as the USDA Forest Service,
oil Conservation Service, USDI Bureau of Land
anagement, Army Corps of Engineers, U.S.
eological Survey, U.S. Public Health Service,
nd various environmental quality enforcement
gencies may be able to provide information.
hose agencies that should be consulted at the
tate level include those that regulate fish, game,
ater, and land use. The names of these State
nd local agencies may vary widely. Finally, area
nd-use plans may also provide information.

## WHAT ARE THE SPECIFIC TREATMENT OBJECTIVES?

Specific objectives should be defined for each task in the reclamation project. For example, regrading may have several purposes including alteration of slopes to reduce erosion, improvement of the visual aspect, and provision of a surface suitable for specific land uses such as recreation and grazing. In addition to being incorporated into the original drafting of site plans, it is important that each of the objectives be understood by the operators performing the task. This is because they may need to make on-the-spot decisions regarding obstacles or other problems that could not be foreseen by the planners. Flexibility such as this, when allowed by planners and project managers, can greatly improve the end result of a project through encouragement of creative input and increased morale on the part of workers at all levels of involvement.

## WHAT KINDS OF ECOLOGICAL CONSIDERATIONS APPLY TO OPERATIONS PLANNING?

A good rule of thumb to apply when planning project operations is to attempt, at each step, to integrate planned land use and the ecological objectives to the project with functional and esthetic design of structures and treatments. Also, it is both ecologically and economically wise to avoid overtreatment of a site. Treatment planning should attempt to maximize the use of existing features, which already provide some of the ecological functions that are project objectives. For example, if the process of natural revegetation is already well established, its destruction and subsequent replanting may be counterproductive unless other objectives, such as extensive regrading for drainage control, make it imperative. Even in such circumstances, alternatives to regrading should be closely considered.

If not already done in the initial planning stage of the project, a wildlife habitat and population inventory should be conducted on the site by a wildlife biologist. Personnel working on the project should then be advised of the results of the survey, including the wildlife present on and near the site and the nature and locations of important habitats. Damage to habitats and their occupants should be avoided whenever possible. However, when destruction of important habitats is unavoidable in the course of treatment, it is a good practice to restore or replace them after completion of the project. Depending on land ownership and other circumstances, restoration and/or other special treatments may be mandated by project approval documents.

## WHAT LEGAL ASPECTS SHOULD BE TAKEN INTO CONSIDERATION IN OPERATIONS PLANNING?

Questions of legality may enter into reclamation projects at several levels including contracting, land ownership and control, rules and regulations, and licenses and permits. In the latter third of this century, the environmental consequences of people's activities have become increasingly tied to our legal system. This section is not intended to give legal advice, but only to point out some of the more common ways in which legal questions may arise with respect to the reclamation of a small mine site. Many situations may require professional legal advice. Chapter 2 discusses several items that have legal implications in the context of initial overall project planning, such as boundary conditions and zoning restrictions. Also, there are legal matters that can affect later stages of planning and/or the actual operation itself. It is not practical to attempt to anticipate all legal questions that may arise in connection with a reclamation project, so only some of the more obvious ones are suggested here.

At the operational level, there are two main components of reclamation projects that may have legal ramifications: the planned effects of the treatment and the incidental "side effects" that affect the site or other land in the watershed. An example of the first situation is the intentional alteration of downstream water quality by reducing the concentration of salts leaching from a tailings pond into the watershed drainage system. Usually, when a change seems positive in nature, it is beneficial and does not generate complaints. If one effect of the treatment, however such as introducing high concentrations of treatment additives, is perceived to adversely affect water quality (albeit inadvertently), l problems could result. Examples of the sec situaiton are the generation of objection noise or air pollution by equipment, or perh an accidental spill of fuel, oil, or other toxic terial into a stream or lake. Of course, there other liabilities that are more traditional in ture, so they are usually covered by insura In some cases, it may be wise to investigate a tional types of insurance coverage for a proj Please note that actual liability may differ, pending on the organization responsible for project.

The potential for legal difficulties can greatly reduced, if certain precautions are served. These include insuring that each per involved in the performance of a project is fa iar with the legal boundaries of the site, as as with certain ownership and jurisdictional c siderations and environmental regulations may apply to the project. In some instances, actual waste materials may extend beyond site's legal boundaries, so workers must be adv of what portions of the dump and/or pond and cannot be treated. They must also underst the need for protecting the treated site f problems caused by the untreated portion, vice versa. Construction of temporary an permanent barriers against such things as hu or animal access, and water flow or earth m ment, may be necessary. In addition, it is im tant that all involved personnel understan many of the potential effects of the various tr ments as possible, both intentional and incide Those working in the field should know poss sources of pollution and how to minimize th In some circumstances, alternative treatn methods may be desirable or necessary to n mize adverse effects.

### Regulations concerning biologi materials

In many states, there are legal restricti concerning the removal and/or introduction various species of plants and animals. In the c of endangered species, special permits and ext sive protective measures may be required. applicability of such restrictions to a partic site or areas in the vicinity should be explair oth in letter and in spirit, to all concerned with project.

## OW CAN ESTHETIC ONSIDERATIONS BE NTEGRATED INTO THE LANNING OF FIELD PERATIONS?

Scenic values and other esthetic aspects of nvironmental quality are of growing importance public awareness and human population in- ease. Esthetic quality encompasses economic, ychological, and social components. Improv- g the esthetic value of a site should be a major nsideration in the planning, treatment, and aintenance levels of a project. Frequently, a te's esthetic quality can be upgraded with rela- vely little impact on the overall cost of a project. tilizing imagination and care in the planning, eatment, and maintenance stages of a project n do much to improve the esthetic value of a te. It is important for all the people involved to aware of the fact that their own artistic sensi- lities and skills will measurably affect the final thetic appearance of the reclaimed land. When- er possible, the assistance of a landscape archi- ct will be valuable and should be obtained.

### lending of form and function

A major principle involved in improving sthetic quality is integrating practical function vith pleasing form. A good rule of thumb to fol- ow is to draw from the strongest elements of he adjacent landscape, such as form, line, color, nd texture. For example, a waste dump is re- raded in a manner that is visually harmonious vith the surrounding landscape, or a fence pro- ided to restrict large animals or vehicles from a ite is both effective and pleasing when con- tructed of wooden rails, rather than chain links r barbed wire. Also, it may be possible to con- truct drainage channels that have the appearance nd function of natural stream beds, rather than artificial ditches. Some of these techniques were successfully used in the Lynx Creek project.

### Utilization of existing features and harmonious construction materials

In many instances, it may be both esthetically and economically desirable to preserve and enhance existing features on a site such as trees, interesting rock formations, established streambeds, and old buildings that blend with the surroundings. For example, existing rocks or boulders might be rearranged in a visually pleasing manner, or even used in constructing walls or retaining structures that would otherwise require introducing nonharmonious building materials from off the site. In addition to being less expensive than new materials, in some cases, building supplies salvaged from old structures can add an "antique" touch to new construction.

### Selection and utilization of vegetation

Revegetation provides another opportunity for blending form with function. For example, trees and shrubs can form fences or traffic barriers. Frequently, ecological considerations may allow a degree of esthetic latitude with respect to species selection and planting arrangement. In instances where vegetation will not grow, a technology exists for altering the color of surface rock so that it blends with its surroundings.

### Utilization of semipermanent treatment structures

In certain situations where it is necessary to erect structures for various reasons including establishing land contours and drainage channels, it may be possible to use semipermanent materials that eventually decay, or that may be removed after sufficient vegetation is established. This use of semipermanent materials will reduce cost and, in the long run, enhance the "natural" appearance of the reclaimed site.

## WHAT FACTORS SHOULD BE CONSIDERED IN THE SELECTION OF EQUIPMENT AND ALTERNATIVE METHODS OF ACCOMPLISHING A PARTICULAR TREATMENT OPERATION?

More than one treatment method or plan may be feasible. These, however, may significantly differ in several aspects, while producing essentially equivalent results.

### Energy use and economic considerations

As our energy resources become more restricted, the cost of a project in terms of energy use will become increasingly important. The economic cost of a project is directly affected by its energy cost. Therefore, the energy cost of alternative treatments and choice of equipment should be carefully weighed. Also, wherever possible, energy-intensive operations should be combined. An example of this is the combination of site recontouring with deep treatment of tailings and waste materials.

### Fire hazard potential

Many abandoned mine sites in the Western United States are in forested areas. The potential for fire hazard should be considered both in choice between treatment alternatives and in selection of equipment. To meet certain standards, motorized equipment may be required. Also, it will be necessary to consider the effects of fire regulations and possible forest closures on work schedules.

### Environmental effects

The environmental effects of treatment and equipment alternatives should be weighed on the basis of their potential for producing pollution such as dust, smoke, and noise.

### Future land use

When selecting treatment methods and making seemingly minor decisions, the planned land use should be kept in mind. For examp small differences in grading, drainage contr methods, or choice of vegetation can be imp tant, if the land is going to be used for recre tional purposes.

## WHAT SHOULD BE CONSIDERE IN THE SCHEDULING OF FIELD OPERATIONS?

Scheduling is one of the most importa and most complex aspects of operations pla ning. Scheduling will have a major effect o both the cost and success of a project. For e ample, unnecessary delays in delivery of materia can be expensive, in terms of idle equipment an operators.

### Sequence of treatments for effectiveness

One of the top priorities in operatio scheduling is planning for any necessary preli inary site treatments well in advance of the co mencement of field operations. For example, the treatment includes reclaiming a tailings pon it must be drained (thoroughly dewatered) much as a year before further operations on i surface. This permits manipulation of the surfa with heavy equipment and allows for settling the waste materials. Also, necessary perm should be obtained well in advance of prelimina treatments.

### Logistical scheduling

There are two major classes of constrai and factors that must be taken into accou those that are fixed, inflexible, or otherwise n controllable, such as climate, seasonal econo factors, and population fluctuations; and th that are adjusted to optimize the flow of eve during the project. For example, climate dicta when grading, chemical treatment, topsoili and planting can be done. Once the major ti framework has been established to accommoda this inflexible constraint, materials, equipme and labor can be scheduled.

## WHAT SHOULD BE CONSIDERED IN THE ESTIMATION OF OPERATIONAL COSTS?

A number of items affect the total cost of a project:

- Administrative costs include those for planning, overhead, and payment of necessary fees and permits. Also to be considered are costs of contracting and general economic factors such as inflation. The effects of inflation should be integrated into long-range cost estimates for site maintenance.
- Site characteristics enter into the determination of cost. The size or the area to be treated is an important variable. For instance, onsite topography and climatic conditions may necessitate construction of drainage and erosion control structures such as gabions, diversions, or spillways. Also, site accessibility and distance will affect the cost of materials delivery. Finally, seasonal changes in accessibility should be considered.
- The quantities needed, price, and availability of materials such as chemicals, topsoil, mulch, seeds, and plants, must be taken into account, as well as labor and equipment costs. All of the above can be drastically affected by changes in local and national economic conditions, which are very difficult to foresee.
- All alternative treatment methods for accomplishing objectives, from waste neutralization to revegetation, should be evaluated for cost, as well as effectiveness. Differences between treatment methods, such as equipment and materials required, can result in large differences in cost.
- Financial responsibility does not end when reclamation treatments are finished. The maintenance costs of fences, access roads, and irrigation apparatus must be considered, as well as the possibility that some treatments such as grading and planting, may need to be repeated.

# Chapter Four

# RECLAMATION TREATMENTS AND PRINCIPLES

## Ecological Problems and Treatment Objectives

Each orphaned mine site will present a unique set of circumstances and problems. Therefore, rather than attempting to present generalized "cures" for all problems, brief discussions explaining the relationship between various site problems and the methods of treatment are provided. In this chapter, topics deemed to be unique or primarily related to abandoned mine sites are covered in greater depth than those commonly discussed in the general literature on mining reclamation. For more detailed technical information on the various topics considered, the reader is referred to the sources listed in the Bibliography.

Generally, most of the ecological and esthetic problems of orphaned mine sites have both physical and chemical components. The physical disruption of the land results in excessive erosion and sediment production, while chemical contamination of the surface soil and water supplies is damaging to vegetative, animal, and human life. Some of the many possible approaches to the cure or containment of these problems are discussed in this chapter.

The overall treatment objectives for an abandoned mine site will vary from site to site. Generally, they will seek to control surface erosion, reduce chemical contamination of underground and/or downstream water supplies, and improve the esthetic appearance of the site. In some cases, the treatment will be designed to reclaim the land for a specific use, necessitating redesign of the landform. Many of the possible treatments address these functions simultaneously. Each mine will present its own unique set of conditions, but most of the above objectives can be met by the following treatments: regrading and filling in badly eroded areas in a manner that is harmonious with the surrounding landscape and suited to the projected land use; chemical treatment designed to reduce the toxicity of mining wastes near the surface; restriction of infiltration of surface waters into the waste materials; installation of structures necessary for the control of erosion and sedimentation produced by water from sources both on and off the site; application of topsoil and mulch to promote a good environment for vegetative growth; revegetation; and protection of the site during the early phase of its recovery. Many of the treatments will be of short or moderate duration, while others may require renewal. The ultimate goal of reclamation treatment is to establish temporary conditions that are gradually supplanted by natural processes. Usually, this goal is realized with the development on the treated site of mature vegetative growth that is ecologically harmonious with that on adjacent land.

## Mine Dumps and Tailings Ponds

The term "tailings" commonly refers to the residue from ore processing operations that is put in a tailings pond (fig. 6). Waste material from underground mining is placed on a dump. There are significant differences between the materials found in waste dumps and ponds associated with a given mine. For this reason, they must be

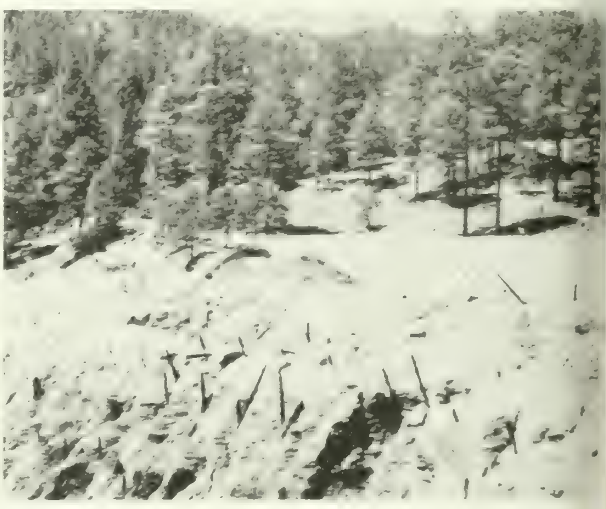


Fig. 6 Tailings pond.

Fig. 7 **Mine dump.**

treated differently. Also, the exact nature of these materials differs greatly with the minerals being mined, the rock in which they occur, and the processing methods used.

Usually, the waste dump of a mine will consist of rocks and other residue from the underground operation (fig. 7). Waste dumps from underground mines are always much smaller, in volume and area, than the tailings ponds from the same mine. In most instances, waste materials from underground mines in the West will be acidic. Often, the materials in a waste dump are found as they were initially piled, at their angle of repose, although in many cases, the original structure may have been considerably modified by erosion. The material at the base of a waste dump is coarser than that at the top, because there is a natural segregation with the coarser and the fine material at the top of the dump.

In mountainous regions of the West, tailings ponds were usually impounded in small canyons or ravines behind dams constructed of mine waste materials. Frequently, the dams were built in stages by increasing their height as the ponds became filled with sediment. Abandoned tailings ponds may or may not contain water, either above or below the surface. The waste materials found in a pond differs considerably from that in a waste dump. Tailings ponds contain the residue from milling and chemical processing of the mined material. Often, the processing chemicals used were toxic, such as potassium cyanide. With time, some of the initial processing materials chemically change or break down, but others may remain in tailings ponds, along with ore residues, for a considerable period of time. Earlier extraction methods were less efficient than more recent ones, so older ponds may have a higher content of residual ore. This is also true of ponds that are gradually filled over a period of time where there is more residual ore at the bottom of the pond. Many ponds have been reworked so that their chemical content may vary in different parts. The consistency of pond waste materials is very fine and tends to be noncohesive If sufficient water is present, waste particles may exist as mud or slurry-like suspensions. In some cases, pond tailings can take on a gelatinous character.

Because abandoned mine reclamation primarily involves working with waste dumps and tailings ponds, an understanding of their nature is important to both planners and those working in the field. Accordingly, additional discussion on this topic is provided in the Appendix.

## WHAT KINDS OF HAZARDS MAY BE ENCOUNTERED WHEN WORKING WITH ABANDONED MINE TAILINGS?

Of course, the exact nature of what remains in orphaned mine ponds and waste dumps over a period of years largely depends on what was being mined. If sulfide residues are present, the tailings may increase in acidity. Probably, this is the major ecological problem associated with abandoned mine sites. Aside from ecological considerations, those involved with reclamation projects should be aware of possible health hazards to workers from the tailings materials. It is good practice to observe appropriate precautions when working with abandoned mine waste materials. Therefore, a safety manual pertaining to the type of mine being reclaimed should be consulted.

An example is the inhalation of acidic dust, heavy metal residues, or silica dust. A further illustration is provided by radium mining operations, which set uranium bearing ore aside in waste dumps. Depending on the water content of a tailings pond and the consistency of the tailings, there may be a potential for spilling or outward flow of waste materials if a dam is breached. The effects of seismic activity should be considered at sites located where this is a possibility.

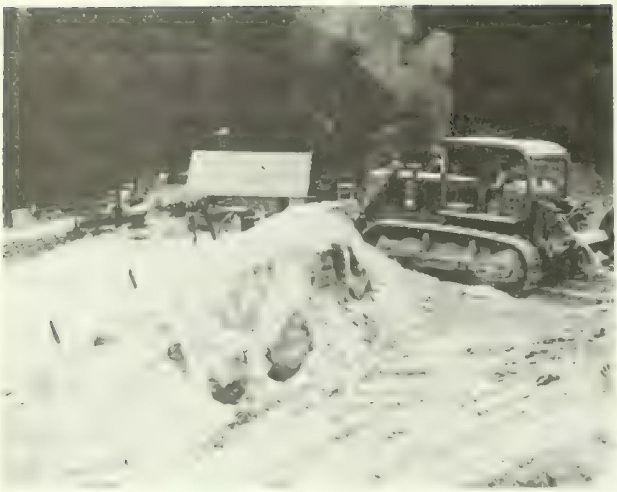


Fig. 8 **Grading of the waste material increases stability, reduces erosion and improves the esthetic appearance of the site.**

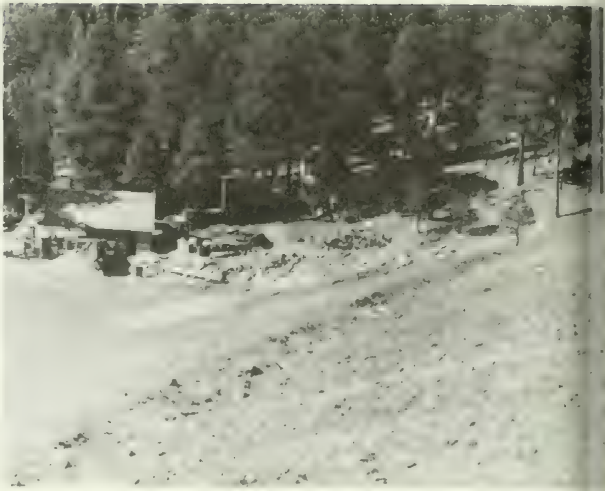


Fig. 9 **The final contour produces dramatic in provement in esthetic appearance.**

Also, in any old, abandoned tailings pond that is 15.24 to 30.48 m (50 to 100 feet) deep there is a possibility of isolated, saturated pockets of tailings that could be a trap for any piece of heavy equipment.

# Physical Treatment of Abandoned Mine Tailings

The two major functions of recontouring mine wastes are to increase stability through reduction of erosion and improve the esthetic appearance of the site. Recontouring can also be tailored to a particular land use. Grading of waste materials can serve to modify or eliminate existing irregularities of form produced by past mining activities and uncontrolled erosion, create slopes that are less severe and more stable, and improve onsite conservation of precipitation (fig. 8 and 9). Also, recontouring can reduce the rate of erosion by decreasing the length and inclinations of slopes. If care is taken to blend the contours with the surrounding landscape, the end result of site recontouring is both esthetically pleasing and utilitarian.

Important components of most reclamation projects include regrading the site and construction of various devices for controlling erosion and sediment production. A variety of structures are possible; however, only a few will be discussed here. For detailed information on the plannin and designing of erosion and sediment contr structures, the reader is referred to the excellen series of EPA publications listed in the Biblio raphy. Control of erosion and sediment by no structural means, such as mulching and revegeta tion, is discussed later.

## WHAT IS THE "OPTIMUM" SLOP FOR RECONTOURED ORPHANE MINE DUMPS?

There is no universal answer to this que tion, but its consideration is of paramount im portance to the success of a project. Unstabl slopes are subject to slipping, which could brin about new exposure of mine wastes, destructio of surface vegetation cover, and loss of topso through rapid erosion.

In most dumps, the wastes are initially pile at the angle of repose for the specific type material. The angle of repose is the maximu slope to which a material will pile and remai stable without surface slides. It is different f each kind of waste material. For example, th cohesiveness of clay is greater than that of san therefore, the natural slope of a pile of clay greater than that of sand. In addition, th moisture content of a material affects its cohesiv ness, permitting damp materials to be piled mo steeply than dry materials.

There are several factors that should be onsidered in the selection of contour slopes: ater runoff; esthetic appearance; and, the procted use of the reclaimed land. The velocity of rface water runoff is exponentially proportonal to both the angle of inclination and length a slope, or the greater the angle or longer the ope, the greater the potential for erosion. In is regard, it is important to consider the innsity and types of precipitation to which the te may be subjected. The intensity of rainfall ents differ regionally. For example, desert and ountain areas in the Southwest regularly exrience heavy rain storms of short duration at can produce rapid erosion, while other reons may be subject to protracted storms of sser intensity or may receive the bulk of their ecipitation in the form of snow. In addition, a te that is to be heavily vegetated can have eeper slopes than one that will remain barren, ecause the presence of ground cover significantly duces surface erosion. The ability of equipment ed for agricultural treatment or maintenance the site to negotiate the slope should also be onsidered in determining the maximum angle r recontouring.

Often, the minimum slope contour is found rough the necessity of containing a given volne of waste material within the confines of the rface area of the site. In most cases, it is probitively expensive, and possibly illegal, to reove waste materials from the treatment site. herefore, the wastes must somehow be rearnged within the legal boundaries of the site so at they will not intersect water courses or uncessarily cover additional areas of undisturbed nd. Remember that the more steeply the waste aterials are piled, the less land area they will over.

In many situations, slopes of 10 to 15 deees are considered optimal with respect to osion, esthetics, and land use. Slopes greater an 30 degrees may create problems; therefore, e rapid establishment of vegetative cover on eeper slopes is particularly important.

## OW CAN WATER FLOW BE ONTROLLED?

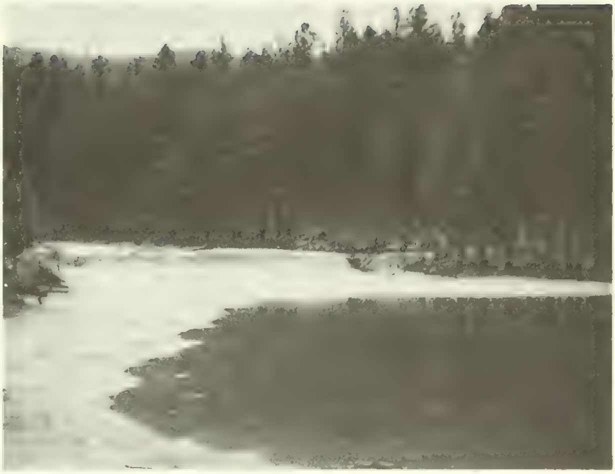


**Fig. 10 Ponded water can create very significant problems and needs to be controlled.**

Two sources of water are controlled in a reamation project: water from off the site; and that which results from direct precipitation onto the site (fig. 10). Onsite water flow is controlled by vegetative cover and surface recontouring, while offsite water flow is controlled through diversion structures, channels, and impoundment structures.

Diversion structures are used to control or prevent erosive surface flow. Some of the methods used include breaking up long slopes that would be subject to rapid flow, and diverting sediment-bearing runoff into traps. The choice of structures depends upon several things including the anticipated water volume and velocity, slope, required structural permanency, ease of installation, and removal. In addition, provisions should be made to withstand 100-year flood conditions, if applicable to the site. Also, it is important to provide protective crossings over water channels for vehicle access, if necessary.

Design details of water diversion and conduction channels are rather complex, so the reader is referred to the aforementioned EPA series on erosion and sediment control for a more thorough treatment of this topic. Basically, channels may be of parabolic, triangular, or trapezoidal design, depending on site conditions, equipment availability, and other factors. The velocity of water flow in a channel will depend upon its size, gradient, surface texture, shape, and course. Protrusions or restrictions in a channel that produce turbulence will restrict water flow and may result in sedimentation or channel erosion (scouring). Erosion of the channel surface

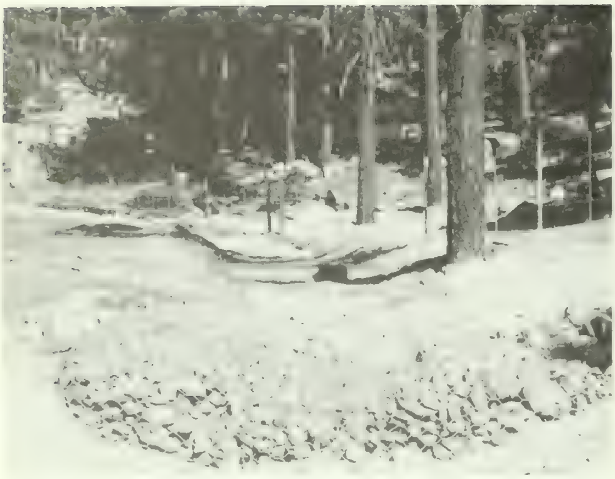


Fig. 11 Gabion Structure.

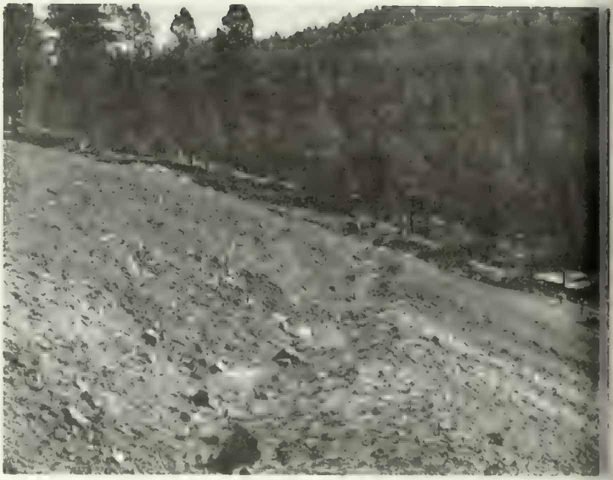


Fig. 12 Diversion dikes help carry off water without erosion.

may be controlled by lining the surface with riprap (loose rock or aggregate) or planting grass in the channel. Erosion of channel banks at curves or intersections, which are subject to the force of high-flow velocity, may be controlled by the construction of straw dikes or gabions (dikes constructed of rock or aggregate baled together with wire mesh). Gabions are highly effective in the Sheldon Mine reclamation project at Lynx Creek (fig. 11). In the case of mineral mines, which produce corrosive or acidic wastes, the wire baskets retaining the rocks should be constructed of stainless steel. This material is available, because it is used in the construction of mill ponds and sea walls. Erosion may be eliminated by lining the channel with metal or concrete, but the expense is greater and such structures can be detrimental to the esthetic appearance of the site. Another way to reduce erosion in channels is through the construction of check dams, which allow control of the rate of water flow.

Overland surface flow is highly erosive to unprotected graded and/or topsoiled slopes and can result in the production of sediment. It may be controlled by creation of surface depressions and roughness, and by breaking up long slope lengths. A number of methods can accomplish this. First, diversion dikes (made of compacted soil) can be constructed parallel to surface contours (fig. 12). Second, diversion swales (ditches) or diversion channels (ditches combined with adjacent parallel dikes placed on the downslope side of the ditches) can also be used. These diversions are constructed along the site perimeter both above a slope to protect the surface from offsite runoff, and below it to intercept an channel sediment-bearing runoff to settlin basins. Horizontal microdepressions and surfac roughness, which will decrease water flow velocity, may easily be produced on moderat slopes by "walking" a caterpillar tractor up an down the slope. This treatment also serves t compact the surface. As soon as possible afte completing the grading phase of an operation mulch should be applied and vegetation planted Adequate vegetative cover provides one of th best long-term methods of reducing surfac erosion. Mulch and vegetation serve to increas surface roughness, reduce the impact of rainfall and increase the water storage capacity of th soil.

## HOW CAN THE PRODUCTION OF SEDIMENT BE CONTROLLED?

Sediment generated by the reclaimed sit may be trapped by the construction of ponds o basins. Sediment traps function by reducing th rate of water flow, which provides time for settling of suspended solids. In mountainous areas the size of sediment traps may be restricted therefore, it is a common practice to construct a series of basins along a water course. Generally these chains of sediment traps are more effectiv than a single large pond of equivalent volume Spillways or perforated risers (vertical pipes wit perforations to allow low-velocity drainage from he pond) may be used as water outlets from ediment traps. These traps can also be installed ithin water channels in the form of barriers onstructed with different materials including andbags, gabions, and logs. Any raised barrier ithin a channel will serve to reduce water ve- ocity and enhance the settling of suspended par- icles. In addition, spillways over sediment traps hould be constructed in such a manner that the ischarge does not produce erosion. Finally, sed- ment traps require maintenance in the form of ccasional removal of accumulated sediment. enerally, this is done when the trap is half full. The removed sediment must be disposed of in a anner that will not result in further erosion. If he sediment does not contain toxic materials, it ay be used as topsoil.

## OW SHOULD TAILINGS PONDS E TREATED?

As previously discussed, tailings ponds in he West are frequently impounded behind dams. n many cases, ponds at older orphaned mine tes may be structurally weak due to poor design nd erosion. Because these dams still function to ontain tailings, it is recommended that they be trengthened as part of the reclamation project, nd that care be taken not to rupture them in he process. If the dam of a pond in a nonarid cation is intact, it is likely that the pond will ontain subsurface water, even if none is present bove ground. For this reason, a pond will require t least partial dewatering before treatment of e surface with heavy equipment. It is recom- ended that ponds be permanently dewatered a level well below the root zone of planned egetative cover. This is necessary to prevent bsurface pond water from transporting toxic aterials into the root zone. It is likely that the ater in a tailings pond contains high concentra- ons of mineral salts and, in the case of acidic aste, has a low pH.

## OW CAN SMALL TAILINGS ONDS (UP TO 4 HA, OR 10 ACRES) E DEWATERED?

Because tailings ponds are of diverse designs, ey may require one or more possible treatments to be effectively dewatered. Usually, this is accomplished by digging one or more ditches into the sediment, then pumping or siphoning the water. An alternative method of drainage is provided by horizontal or vertical wells, but vertical wells require mechanical pumping. By whatever means the dewatering is accomplished, the water will probably require treatment before it can be released into the watershed, because it is likely to contain high concentrations of soluble salts and other chemicals. Therefore, it is important that tailings pond water be analyzed prior to draining. If the chief treatment of the water is to be pH adjusted, the water can be run through filter ponds or tanks containing lime or gypsum. As previously mentioned, pond dewatering should be done as much as a year in advance of further treatment to allow sufficient surface stabilization for the operation of heavy equipment.

Permanent dewatering of the root zone is accomplished by placing drainage pipes in the dam, or around its edges, at an appropriate level, then recontouring the pond surface with earth fill (perhaps obtained from a nearby waste dump), to give it a convex shape. If any portion of a dam is removed, it should be done only after dewatering. The purpose of the domed shape of the pond surface is to reduce the collection and infiltration of surface water into the pond. The new surface is then treated and topsoil is added. Also, the pond can be protected from offsite water by the appropriate placement of adequate diversion channels. Because many ponds are located in the bottoms of canyons and ravines, diversion channels should be of sufficient size and construction to handle runoff from intense storms without erosion of channel walls. Adequate systems can be designed by hydrologists and engineers, who first analyze the potential runoff magnitude.

Probably, the best way to strengthen a tailings pond dam is to reenforce it from the front with earth fill. This operation can be combined with the recontouring of a site, effectively burying the dam (fig. 6).

## HOW CAN LATERAL MOVEMENT OF OFFSITE UNDERGROUND WATER THROUGH WASTE MATERIALS BE CONTROLLED?

The problem of controlling lateral underground water movement from off the treatment site through waste materials is a difficult one. This situation was encountered at the Sheldon Mine. The gravity of the problem is compounded by the fact that such flow may be at a depth well below that at which chemical neutralization of the wastes is possible. Restriction of this lateral water movement through a waste dump or tailings pond depends upon certain conditions such as subsurface geological conditions and the source of water. In some circumstances, the water source may be blocked by sinking a retaining wall into the lower limit of the aquifer where, in other situations, it may be possible to divert the water flow using horizontal wells.

A related problem concerns the drainage of ground water from underground lateral workings. A common way to treat this situation is to seal the offending working by drilling vertical holes into it at intervals, then plugging it with concrete or "bentonite." Sometimes, the source of water is a vertical shaft, which passes through water-bearing strata. In this case, it may be possible to plug the vertical shaft. The control of drainage from underground mines is detailed in the EPA publication on inactive and abandoned underground mines which is listed in the Bibliography.

# Chemical Treatment of Abandoned Mine Tailings

## WHAT CHEMICAL CONDITIONS MAY BE FOUND AT THE SURFACE OF ABANDONED MINE SITES?

Generally, the chemical nature of waste materials is unique for each mining site, depending on local surface and subsurface composition, the nature of the ores that were mined at the site, and any extraction procedures that might have been carried out during the operation of the mine. The tailings of some mines may have been reworked at more than one period in history, each time altering and restratifying the chemical composition of the surface waste materials. It is important to note that the physical and/or chemical soil structures and chemical compositions of waste dumps and tailings ponds are not homogeneous. Core samples taken at various locations on the surface of a waste dump or tailings pond can indicate considerable variation in chemical composition with respect to depth and horizontal postion, reflecting the operational history of the mine. For this reason, it is possible that different treatments will be required for different zones in a single waste dump or tailings pond.

There are two major classes of soil chemic conditions that may cause ecological problems at a site: excess alkalinity or acidity; and, the presence of heavy metal salts or other toxic chemicals. Many plants are highly sensitive to soil pH conditions that deviate from 7 (neutral For example, acidic soils have a pH value lower than 7, while alkaline soils have pH levels above 7. While plants differ with respect to their "preference" for pH, most will grow well in the range between pH 6 and 8. A few will tolerate conditions of greater alkalinity or acidity.

Two main objectives in treating chemical conditions in orphaned mine wastes are attempting to neutralize pH extremes and detoxifying poisonous salts and metals occurring near the surface of the wastes that could contaminate the topsoil; and preventing percolation of large quantities of surface water through the waste materials that will leach chemicals from the tailings and contaminate underground or downstream surface waters. For the first objective, soil pH can be adjusted through the addition of amendments. For instance, lime will act to neutralize acid conditions, while alkaline soils can be treated with gypsum. Poisonous salts and metals, however, must be treated by specific methods. In both situations, efforts are made to physically separate the topsoil layer from the toxic waste materials. The second objective, reduction of water percolation through the tailings, is approached through a combination of physical manipulation of the site and its surface, addition of soil amendments, and planting of vegetative cover. Another component to the problem of vater supply contamination which, in many instances, is very difficult and/or expensive to reat, is the lateral flow of underground water rom offsite sources through the waste material. 'his problem is briefly discussed in the section n the physical treatment of mining wastes.

# Treatment of Acidic Wastes

Acidic wastes and drainage from them can e highly detrimental to the ecology of a waterhed. Terrestial plant life is adversely affected nd the balance of aquatic ecosystems can be isrupted to the extent of making water in lakes nd streams uninhabitable for fish and waterwelling plants. Acidic wastes are usually treated vith lime, but, in some areas, it may be possible o regrade the site with alkaline topsoil, if it is vailable. The technique of alkaline regrading is iscussed in the EPA book on inactive and bandoned underground mines, which is listed in he Bibliography.

## VHAT FORMS OF LIME CAN BE JSED FOR TREATING ACIDIC MINE VASTES?

In agricultural practice, lime is used to neuralize highly acidic soils to increase their suitbility for plant growth. Lime is invaluable for reating soils in regions receiving large amounts f rainfall, where water has leached basic salts rom the soil, leaving acidic residues behind. The ddition of lime affects the soil physically, hemically, and biologically. This is because lime ncourages a granular soil structure and stimuates organic decomposition and the production f humus. These effects combine to encourage he growth of legumes and other deep-rooted lants.

Lime comes in several forms that differ in rength and stability. It is important to know omething of the differences between the three ajor forms of lime, because they must be used nd handled in different ways to be properly efctive. For agricultural use, lime is manufactured om a number of sources, including pulverized r ground limestone, oyster shells, or certain industrial byproducts. The following are different types of lime and how they are produced. Lime oxide is often called quicklime or burned lime, because it is manufactured by heating limestone in kilns. Slaked lime is sometimes erroneously called hydrate. It is produced by adding water to burned lime. Both quicklime and slaked lime are kept in bags to maintain their purity, because they can absorb water from the air. Also slaked lime can take up carbon dioxide from the air and thereby lose its strength. Carbonate of lime is simple ground or pulverized limestone, oyster shell, or bog lime. It is also obtained from other sources. Calcite (calcium carbonate) and dolomite (calcium magnesium carbonate, sometimes called dolomitic limestone) are two additional forms of lime carbonate. Quicklime is more caustic than other forms, so it should be handled carefully.

Ground limestone (carbonate of lime) is effective in increasing crop yields (Brady 1974), and is the most popular form of lime for this purpose. However, a more concentrated form may be preferable for treatment of highly acidic mine waste materials. The chemical purity, strength, and stability of lime varies with the type, physical constituency, and method of manufacture. It is important to note that lime changes chemically once it is added to the soil, possibly affecting its treatment effectiveness. Lime oxides are commercially guaranteed on the basis of their neutralizing power, calcium oxide content, or the relative percentages of calcium and magnesium. Ground limestone is usually guaranteed according to carbonate content or its neutralizing power. The interpretation of lime potency is somewhat complex, so the reader is referred to the text by Brady (1974) listed in the Appendix for further information. As a rule of thumb, however, 1.0 ton of finely ground limestone is roughly equivalent in neutralizing power to 0.7 ton of slaked lime and 0.5 ton of quicklime.

## WHEN SHOULD LIME BE USED AND WHAT TYPE SHOULD BE SELECTED?

Deciding whether or not to use lime on a site largely depends on the soil acidity of pH. First, the pH of both surface and subsurface samples is determined. If the pH is 6 or less, the application of lime is recommended. Once a decision is made to use lime, the choice of the type of lime is generally based on five factors:

1. Chemical guarantee of the limes available,
2. The cost per ton of applied lime,
3. The rate that the lime reacts with the soil,
4. The constituency of fineness of the lime,
5. Costs of storage, handling, etc.

For a detailed discussion of these points see Brady (1974).

## HOW IS THE PROPER AMOUNT OF LIME DETERMINED?

The amount of lime that is required to reduce the pH of waste materials near the surface depends on a combination of factors including the surface and subsurface pH; texture, structure, and organic content of the material to be treated; the kind and fineness of the lime; the pH requirements of the vegetation to be planted; and various cost factors (Brady 1974).

Highly acidic mine wastes require much higher concentrations of lime than agricultural soils. It is recommended that soil samples from mine waste materials be analyzed in a soil chemistry laboratory and tested to ascertain the amount and type of lime required to raise the pH to the desired level. Because waste dumps and tailings ponds are not homogeneous throughout, it is desirable to take a number of samples for pH and chemical content determination, carefully noting the surface location and depth of the sample.

Overliming (application of too much lime) raises the soil pH beyond the optimal point for plant growth. Also, it can lower the ability of plants to take up minerals. As plant species differ with respect to soil pH tolerance, the defined point of overliming varies. The danger of overliming, however, is greatest in sandy soils, which are low in organic content and have less capacity to "buffer" or accommodate the strength of the lime than heavier soils. In addition, it should be noted that certain plants, such as blueberry, laurel, and rhododendron, require acidic soils, because their growth is retarded by the use o lime.

## BY WHAT METHODS CAN LIME B APPLIED TO MINE WASTES?

To obtain rapid neutralization of the soil the lime should be applied to land that is plowed Then the lime is worked into the soil during preparation for planting. Alternatively, the lime may be applied to the surface, then plowed under, but this method is slower acting. The long-range effects, however, are equivalent to those produced by the first method, and it ha the advantage of permitting bulk spreading o the lime. In agricultural practice, lime application is sometimes incorporated into the seeding process, but the higher lime concentrations that may be required for neutralizing mine wastes could be harmful to the seeds. The season in which lime is applied is not important, but sequence in treatment is. Hydrated lime requires time to work into the soil, so it should be applied well in advance of planting, while ground lime can be applied 24 hours before planting. If lime is to be plowed into the waste materials, the root depth of the plants that will be used for revegetation must be considered.

Also, lands to be reclaimed following mining operations differ from agricultural lands i that the problem to be treated extends far below the soil surface, and the acidic content of th wastes is much greater. Therefore, greater quantities of lime are required for treatment, and simple topical application of the lime may no produce the necessary effect. Because the pH may vary at different sites on the tailings surface it is important to consider differential treatment with respect to the strength and quantity of lim required. If regrading of the waste material i part of the treatment, it may be worthwhile t consider combining the lime application wit the regrading process. This extends the lim treatment to a greater depth. Alternatively, hole may be dug or drilled into the surface at regula intervals and filled with lime. This method allow gradual lateral distribution of the neutralizing effect of the lime over a period of time (fig. 7 Other methods of effecting subsurface soil treatments may suggest themselves in the course of project.

Finally, soil pH monitoring should be interated into the overall postreclamation project anagement program. Supplemental lime treatents by one of the suggested methods may be ecessary, if lateral or vertical subsurface water ovements carry acidic materials into the surface il.

# Treatment of Alkaline Wastes

In regions of the Western United States here rainfall is limited, alkaline soil conditions ften predominate and are sometimes associated ith mine wastes. In general, drainage from alkaline mines or waste materials is not as environentally harmful as that from acidic wastes and ines. An alternative to treatment of mildly lkaline wastes is to plant them with salt-tolerant egetation.

## OW CAN SOIL ALKALINITY BE REATED?

Treating alkaline or saline soils may be aproached in three ways: eradication of the salts; onversion of the salts to less harmful forms; nd control of salinity through a management rogram. In agricultural situations, the most ommon treatment is eradication of the salts by nderdraining the soil, or applying excess water o flush or leach the salts from the soil. Converion involves changing insoluble salts to soluble orms through the addition of chemicals, such as ypsum, then leaching the soluble salts out of he soil. Control programs are aimed at reducing vaporation to retard upward movement of salts hrough the soil into the root zone. Because this pproach tends to be expensive, other alternaives are often used including programs of freuent irrigation to dilute salinity during critical eriods of plant development or using salt-reistant varieties of plants. When treating abanoned mine wastes, conversion utilizing gypsum probably the most effective and economical of he three approaches in dealing with soil alkalinty.

Gypsum is a sulfur-containing salt (hydrated ulfate of calcium). It chemically reacts with inoluble alkaline carbonates, converting them into soluble alkaline sulfates, which may then be leached from the soil. Generally, several tons of gypsum are applied per hectare (acre). It should be cultivated into the soil, rather than plowed under. Because water is necessary for the chemical reaction to take place, the treated soil should be kept moist. After a period of time, the treatment is followed by thorough irrigation to leach some of the soluble alkaline salts from the soil. Please note that using gypsum without adequate water treatment may be hazardous.

It is also possible to treat alkaline soils containing sodium carbonate with sulfur. Sulfuric acid is produced and acts to both neutralize the alkalinity of the soil and produce sodium sulfate, a neutral salt that is relatively harmless in the soil.

# Topsoiling

Usually, abandoned mine-waste materials are so sterile or highly toxic that they cannot support plant life, even after they are treated on the surface. In order to provide a suitable substrate for the restoration of plant life, it is necessary to cover these wastes with a layer of topsoil taken from another location. Unlike modern stripmining operations that are required to remove and set aside topsoil before removal of the overburden, abandoned mine wastes have been dumped on the topsoil, making its replacement necessary.

## WHAT SHOULD BE CONSIDERED IN THE LOCATION AND SELECTION OF TOPSOIL?

Generally, selection of a source of topsoil is made on the basis of its properties and availability. Locating a source of good quality topsoil can become a problem. In some situations, procurement of high-quality topsoil requires considerable political expertise and negotiation, because the topsoil is permanently "borrowed" from the donor site. This site may require reclamation treatment after the topsoil is removed. In some areas, environmental regulations prohibit such borrowing. Further, the distance that topsoil must be hauled directly increases the cost of the project. Too much compromise with respect to topsoil quality can adversely affect the success of the entire reclamation project.

When selecting topsoil, the best rule of thumb to follow is that it should closely approximate that on undisturbed land surrounding the reclamation site. Topsoil should be selected for its texture, available water holding capacity, organic content, workability, spreadability, and tilth. It is important to have topsoil tested in a soil chemistry lab for suitability before it is borrowed. In general, loam is preferable to alluvial material with high sand and/or gravel content. Less desirable are silty soils, which tend to crust. Rocks may be desirable, however, because they can be worked into the surface, serving both to anchor the soil and provide small surface disturbances fostering vegetative growth. Finally, the quality of topsoil may deteriorate if it is stockpiled for periods exceeding 3 months.

## HOW DOES MULCH FUNCTION AND WHAT TYPES ARE AVAILABLE?

The surface of the reclaimed mine site must be able to absorb and hold sufficient moisture for sustained vegetative growth. Too much water, however, will leach toxic salts from the waste materials into the underground water table.

Applying mulch before, along with, or following the seeding operation accomplishes several purposes. One of the most important is its function of reducing soil detachment and erosion by precipitation and wind, thereby creating a stable environment for germination and growth of the new vegetation. Also, mulch provides insulation against excessive heat or cold, increases organic matter in the soil through decomposition, helps retain moisture in the soil, and affects soil surface microclimate and nutrients available to the germinating seedlings. Finally, mulch is used to control soil temperature, because the addition of dark-colored mulch increases absorption of heat from the sun and warms the soil, while light-colored mulch reflects heat and serves to protect the soil from overheating.

Several types of mulch are available including straw, wood, or paper fiber mixed with asphalt emulsion and water (hydromulch). Cement and other commercial binders are also use Plastic emulsions are marketed, but these are re ommended more for soil stabilization when vegetation is not a goal, because they form sturdy crust, which seedlings have difficul breaking. Other fibers such as ground newspri rice hulls, and cubed alfalfa have been used, b are not as satisfactory as wood fiber. Wood fib stays in place for periods of up to a year, even areas with high slopes, and has been shown to effective in reducing germination time and i creasing seedling survival rates. Also, straw highly effective, if it is suitably tacked to t surface or crimped. Additional information mulching may be found in the EPA reference erosion and sediment control listed in the Bib ography.

# Fertilizing

## WHAT CRITERIA SHOULD B APPLIED TO THE SELECTION C FERTILIZERS?

Generally, fertilizers are selected on the sis of laboratory soil analysis. This analysis det mines which nutrients are totally lacking fr the topsoil in which the plants are to be plac and which nutrients need to be augment Usually, a soil lab is prepared to recomme which fertilizers will be best suited for the conditions and plant species to be used. Al the lab makes recommendations on the amou of fertilizer to apply. For further informati see the EPA reference on erosion and sedim control listed in the Bibliography.

# Revegetation

Compared to the eastern portion of United States, revegetation of mined lands in West is difficult, because three-quarters of land receives less than 51 cm (20 inches) of cipitation annually, and is subject to comp tively great diurnal and seasonal temperature tremes. In those areas receiving snow after ground has frozen, much of the precipitat runs off. Also, in regions of low humidity, s sublimes (is converted directly to water va d again, the moisture is not taken up by the il. Therefore, in many areas in the West, reveg- ation efforts must use species that can survive ith little moisture. Special efforts must also be ade to assist the plants in becoming established. enerally, it is best to use species that are native the region and adapted to local conditions.

The first objective of site revegetation is to ovide soil stabilization as rapidly as possible. his is best accomplished by first mulching, then anting a mixture of rapid-growing grass species mbined with legumes that will offset the trogen deficiency common to most mine-waste aterials. Once the regraded waste surface is itially stabilized, additional planting is done, orking toward creating a long-term vegetative ver.

An important general consideration in re- getating all sites is that seeds, sprouts, and edlings (as well as adult vegetation) must be otected from animal and human damage. razing animals can be particularly detrimental.

## HOULD SUCCESSIONAL R CLIMAX PLANTING E USED IN WASTE ATERIAL-REVEGETATION?

Three major alternatives may be followed ith respect to reclamation-site revegetation ith native plant species: successional planting; imax planting; or a combination of the two. imax planting refers to initial planting of the claimed area with identical or similar species those growing on undisturbed land immedi- ely surrounding the treatment site. The term ccessional planting describes the practice of rst planting species that easily become estab- hed, then preparing the site for the gradual in- oduction of climax vegetation through various tions including developing improved soil con- tions and ground cover. Conditions on the eated site may not support climax planting ithout extensive preparation, particularly if the cal climax growth consists of deep-rooted trees. urther, there are two reasons to question hether climax planting will ever attain its ulti- ate goal. First, waste materials that underlie e topsoil on the treated site are significantly fferent from the subsoil conditions that exist off the site, so it is probable that surface soil will not develop on the treatment site in the same manner as off the site. Second, the term vegetational "climax" does not necessarily refer to a permanent condition. The ecological conditions that control climax growth gradually change with time, and the local climax type may change. Therefore, one cannot predict with certainty that the growth on the reclaimed site will ever "catch up" with the surrounding vegetation. In arid regions of the West, native plant species and communities are characterized by slow growth and development.

The third alternative, which is recommended for the revegetation of abandoned mine wastes, is to devise a planting program that combines aspects of both climax and successional planting by initially stabilizing the site with rapid growing cover species and then artificially preparing localized sites for climax species. The first objective is accomplished by planting a mixture of rapidly growing grasses and, perhaps, shrubs such as mustard. In arid or semiarid areas, these plants require assistance in the form of irrigation. Later, this initial growth can be augmented by planting larger shrubs and/or trees in specially prepared sites that offer soil of sufficient quality and depth to promote and protect the deeper root growth from the toxicity of the underlying waste materials.

## WHAT CRITERIA SHOULD BE USED IN SPECIES SELECTION?

Plant species for the revegetation of abandoned mine sites should be selected by several criteria. The most important of these is potential for survival in the local climate. All other variables, including soil conditions, can be at least partially controlled. In general, locally occurring vegetation is better adapted to an area than introduced species. In the arid and semiarid regions of the West, growing conditions vary considerably with altitude, slope aspect, and temperature. A variety of conditions can exist within a small radius.

The next most important criterion is the suitability of the selected plants to the soil conditions that are created on the surface of the mine wastes. Soil pH and salinity are both important factors to take into account; however, many species exist that are relatively tolerant of extremes of soil pH and salinity.

In addition, rapid growth rate and soil conditioning capabilities are important factors in species selection. For instance, legumes are important, because they provide nitrogen, which is deficient in mine waste materials. Also, they have tap roots and can incorporate organic material into the soil at the greater depth, than do grasses. In addition, some species of shrubs produce a high amount of litter, which increases the organic content of the soil. Another important consideration is the interactive effects between plants. The dead foliage of some species secretes materials that are toxic to other plants, discouraging growth beneath them.

Most of the additional criteria for species selection is function related, such as potential for soil conditioning, soil stabilization (the root systems of grasses have excellent soil-holding capabilities), forage, shade, and esthetic quality. In some areas, there may be legal restrictions on certain species. For example, in Arizona, it is illegal to plant morning glories, because they are deemed a threat to cotton crops. Probably, the best source of specific information on optimal species for the conditions at a given site is a botanist or plant physiologist at a local university, who can make a determination based on an analysis of the site conditions, combined with a knowledge of regional species. Also, soil conservation technicians may provide information, if there is a local Soil and Water Conservation district office. There is abundant literature on the revegetation of mine wastes, but much of it is based on experience in the eastern portion of the nation where conditions and predominant plant species are significantly different from those in the West. The reference by Doyle, listed in the Bibliography, discusses the problem of revegetation of mined land in the arid and semiarid regions of the West.

In regions receiving little rainfall, it may also be desirable to plant different species of vegetation on north- and south-facing slopes. This pattern can be observed in natural vegetation, and is predominantly due to differences in soil moisture resulting from exposure to the sun. If this pattern is followed in revegetation of an area where it would naturally occur, the long-term chances survival of the new growth may be improved.

## WHAT METHODS OF SEEDIN AND PLANTING CAN BE USED FC REVEGETATING MINE WASTES?

### Seeding techniques

In most instances, seeding methods co monly used in revegetating stripmine taili may be used on abandoned underground m sites. These might include hydroseeding, bro casting by use of blowers or cyclone seeders, a hand seeding. The chances of successful germi tion will be increased if the surface is not c turbed after planting. Natural seeding, such leaving revegetation of a site to nature, probal will not result in rapid site stabilization. Seed techniques are discussed in a number of boo on mine reclamation, including Thames (197 listed in the Bibliography.

A number of factors affect seed germi tion. Soil moisture and temperature are two the most important. Seeds that are soaked o night in water before planting germinate m quickly than seeds that are dry immediately p to spreading. A common practice is to spr seeds with mulch. Please note that optimal temperatures, as well as temperature tolera limits of seeds, vary with different species. G erally, germination and growth is faster if d time temperatures are warm; however, soil t peratures over 38° C (100° F) can be detrimen to some species. The temperature of the soil s face can be controlled by its color. For examp dark soils can become very hot. This can compensated for by utilization of a light-colo mulch. Alternatively, cold soils can be warm with dark-colored mulch.

### Planting techniques

Usually, direct seeding of trees and shru is not effective under the arid conditions preva ing in many areas of the Western United Stat They must be transplanted at advanced stages development, or planted in the seedling stage. trees are to be planted and the topsoil cover o the waste material is shallow, pits at a depth a iameter up to 1.2 m (4 feet) must be excavated ito the waste material, lined with a protective yer of lime (for acid tailings), then filled in ith a mixture of topsoil, mulch, and fertilizer. variety of seedling containers are available in hich the seedlings may be directly planted.

Trees and shrubs may be planted in semi-id regions in condensation traps. These are onstructed by covering the basin in which a edling is planted with a plastic sheet. The sheet i sealed around the perimeter of the basin with il cover and rocks, while the plant projects trough a hole in the center. Rocks are then aced on the plastic sheet around the plant to eight the plastic down into a funnel shape. aporating soil moisture is condensed on the eet, then it runs toward the center and drip irgates the plant. This structure also functions to llect rainwater that falls near the seedling. ore information about these devices can be und in the water harvesting reference by Aldon d Springfield (1974), listed in the Bibliogphy.

Additional methods of planting in arid gions include using tubelings and supplemental ot transplants. Tubelings are nursery seedlings at have been grown in 2-ply paper tubes apoximately 6.4 cm (2.5 inches) in diameter. hen the tubelings reach a certain size, they can planted (still in the tube) in auger-drilled les. After planting, the tubes are sealed around e top, then the plants are allowed to develop thout further attention. A variety of plantable edling containers are now available. Suppleental root transplants involve planting two nnected rhizomatous shrubs in a single hole. e top of one of the plants is removed and its ot system is planted in deep moist soil, while e other plant is placed normally in drier soil ar the surface. Then the plant with the foliage aws moisture through the rhizome from the ot system of the deeper plant. These methods e discussed in the book by Doyle (1976), listed the Bibliography.

It has been found that many plant species ve symbiotic associations with microscopic ngi. The fungi assist the plant roots in the upke of water and certain nutrients. Research incates that certain species of shrubs, which ocr in the West, demonstrate improved growth soil that has been innoculated with mycorrhizae. Species benefiting from such an association may have an advantage in becoming established on reclaimed mine wastes in areas where moisture is limited. Readers interested in more information regarding this subject are referred to an article by Aldon and Springfield in the book by Thames (1977), listed in the Bibliography.

# Irrigation

## IS IRRIGATION OF REVEGETATED MINE SITES NECESSARY?

Depending on site conditions, species selection, and planting methods, irrigation may be necessary for the first year or so, until plants become established and can survive under natural moisture conditions. One major reason for recommending native vegetation species for revegetation is to avoid the need of prolonged irrigation. In many arid or semiarid areas, however, temporary assistance in the form of irrigation may be required. Alternatives to irrigation, such as special planting techniques, are discussed in the section on planting methods.

Of the various forms of irrigation available, drip irrigation is probably one of the best adapted, due to its potential for water economy in remote arid sites; however, it provides highly localized coverage and is not suited to the establishment of grass cover. In the latter case, periodic sprinkling is probably the method of choice. Whatever the method used, the system should be designed for the task and carefully maintained. Various aspects of irrigation are discussed in an article by DeRemer and Bach in the book by Thames (1977), listed in the Bibliography.

# Chapter Five

## POSTTREATMENT MONITORING AND MANAGEMENT

The ultimate goal of a reclamation project on an orphaned mine site is to achieve a state of ecological and esthetic equilibrium and harmony with the surrounding landscape. In this state, the site will be ideally stable and maintenance free with respect to various conditions including erosion and vegetation. Since soil stability is, in most cases, dependent on the successful establishment and maturation of permanent vegetative cover, stabilization may require several years to achieve. In the period that intervenes between site treatment and the development of a state of self-maintaining stability, a program of monitoring and management is ususally necessary. The monitoring program should include land located both above and below the site in the watershed.

### WHAT PROVISION CAN BE MADE FOR CONTINUED SITE MAINTENANCE IN THE EVENT OF A CHANGE IN LAND OWNERSHIP?

Because some sites may require considerable time to achieve a state of equilibrium, provision for continued site protection and maintenance in the event of a change in land ownership may be necessary. The circumstances surrounding the initiation of a site reclamation program can vary considerably depending on land ownership and the nature of the problems presented by the untreated site. Generally, an agreement for continued maintenance can be incorporated into a deed covenant. In most instances, it is advisible to obtain the assistance of an attorney in this matter.

### WHAT SHOULD BE INCLUDED IN A POSTTREATMENT SITE MONITORING AND MAINTENANCE PROGRAM?

### Erosion control

The site should be inspected periodica
and after heavy storms for signs of surface wat
erosion and/or damage to erosion control stru
tures. In addition, water handling structur
should be inspected for breaks, damage to wal
and collection of sediment and vegetative debr
If found, damage must be repaired and sedimen
removed. Also, sediment trapping devices requ
cleaning, when approximately half filled. D
pending on its quality, sediment should be d
posed of in such a way that it will not ero
again, or it might be used for supplemental to
soil. In addition, site access roads must be
spected and maintained. If wind erosion is
problem, the site may need to be sprayed w
water or other stabilizing materials, until stab
ity can be achieved with vegetation.

### Vegetative cover

Vegetation can be monitored by visual
spection, along with a program of making
riodic photographic records. Photographs
most effective for this purpose if regularly tak
from established points for comparison. If grow
of the vegetation is lagging, soil moisture a
quality analysis is advisable If required, irrigat
should be adjusted and/or supplemental fertili
applied. In addition, particular attention sho
be paid to soil pH. If changes in pH are fou
they require immediate correction by additio
soil amendment treatments, before the soil
comes toxic to vegetation. Generally, subsurf
treatment (amendment filled, regularly spac
auger holes) will be more effective in the lo
run, than surface application methods.

If the planted vegetation does not ta
hold within a reasonable period of time, a s
analysis should be performed. If soil quality
good and if sufficient water has been appli
the suitability of the planted species for the
vironment on the site should be considered. I

anting with alternative species may be indi- ted.

## Water quality

Ground and stream water quality must be gularly monitored. Stream water samples ould be taken at points located immediately ostream and downstream from the site and ompared. It is a good idea to take samples at veral points downstream to detect possible derground flow into the stream.

Water quality may not improve immediately ter treatment of a site that had been producing oblems, but continued lack of improvement ver a period of several months may indicate at the treatment is not sufficient. In this case, ossible existence of additional untreated sources polluted water from the site (such as drainage om unblocked lateral workings) should be con- dered. Another possibility, particularly in the se of tailings ponds constructed in canyons d ravines, is the existence of underground ater flow from the surrounding canyon walls ssing through the tailings material and into the wnstream surface or underground water sup- ies.

# GLOSSARY OF SELECTED TERMS

Angle of repose: The maximum steepness of slope at which a pile of material, such as sand, dirt, or mine waste material, will remain stable without sliding.

Loam: A soil containing a moderate amount of sand, silt, and clay. Generally, loam soils contain less than 52 percent sand, between 28 and 50 percent silt, and from 7 to 27 percent clay.

Mulch: A layer of organic material derived from the residue of plants or inorganic material that is applied to the topsoil surface to create a more favorable environment for the establishment of vegetative growth.

Spoil: Non-ore material that overlies a mineral deposit and must be removed in surface mining to gain access to the ore. This term does not properly apply to the waste materials of underground mines.

Tailings: Debris or unused ore material remaining after the available minerals are removed from the ore by treatment.

Tilth: The physical condition of the soil with respect to plant growth. Soil "tilth" refers (among other things) to its stability, granulation, moisture content, capillary water holding capacity, rate of water infiltration, drainage, and degree of aeration.

# Appendix

## ADDITIONAL COMMENTS ON THE NATURE OF TAILINGS PONDS AND WASTE DUMPS

In most instances, mine wastes and/or tailings are the focal point of reclamation efforts on abandoned mine sites. An understanding of their structure and content is valuable to reclamation project planners and workers. More detailed information on this subject is found in several of the references listed under Mining Information in the Bibliography.

Tailings in many of the older ponds at mines that have seen periodic activity over a number of years may be stratified with the older materials at deeper levels, reflecting the operational history of the mine. Processing techniques for many minerals have significantly improved over the years, greatly increasing extraction efficiency. Milling methods of a century ago produced tailings having the consistency of sand. Today, the particle size of tailings approaches the fineness of talcum powder. A modern process, differential flotation, permits recovery of minerals that were formerly discarded in tailings and other wastes. For example, in copper mining, it is now possible to economically separate molybdenum, gold, and silver. Previously, these were passed on to the tailings pond. Depending on the type of mine, processing chemicals may have also changed, resulting in stratification of pond chemical content. In many instances where the mineral content of older tailings and wastes was sufficiently high, the ponds and dumps have been reworked, perhaps more than once as technologies continued to improve. Depending on the methods and thoroughness of reworking operations, the pattern of vertical stratification of wastes may have been completely or partially disrupted. Important to reclamation efforts is the fact that such alteration may mean that the nature and concentrations of toxic materials in a given dump or tailings pond may differ from one location to another. This can materially affect the nature and/or intensity of treatment necessary for revegetation of the pond or dump surface, because various portions of a pond's surface may require different treatments.

Some abandoned mines may not have large waste dumps. The mining process of block caving, where ore is removed from beneath through a side tunnel, results in caving in of the surface material overlying the ore deposit. This material would have otherwise been placed on a waste dump. However, such mines can produce large tailings ponds.

The chemical content of tailings depends on the minerals mined and extraction methods used. Some processing chemicals are extremely toxic. For example, a technique employing cyanide compounds had been used in some gold operations. The chemicals in the pond may undergo further reaction over long periods of time, thus changing their character. It is recommended that safety information specific to the particular materials mined and processed at a site be consulted in the planning stages of a reclamation project.

In addition, the overall structure of dumps and tailings ponds largely depends on the terrain of their location and the proximity of water. Also, the dams of old tailings ponds may not be structurally sound. Frequently, small dams were constructed across side canyons, and as the ponds filled, the dams were extended in stages. In some cases, these dams may have been poorly engineered. Structural reinforcement of such dams prior to reclamation should be considered, because dam failure is a possibility. Abandoned dumps with *no water retained* tend to become stronger as they dry.

In arid regions, tailings ponds may be completely dry, but where a pond still contains surface or subsurface water, the consistency of the tailings may pose potential problems. In some ponds, the tailings may be suspended in a gelatinous or colloidal state or be present as a fine mud. Such ponds may be potentially hazardous until they have been adequately dewatered.

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KEY WORDS: reclamation, tailings ponds, mine dumps, Western United States.

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KEY WORDS: reclamation, tailings ponds, mine dumps, Western United States.

## THE SEAM PROGRAM

The Surface Environment and Mining Program, known as SEAM, was established by the Forest Service to research, develop, and apply new technology to help maintain a quality environment while helping meet the Nation's mineral requirements. SEAM is a partnership of researchers, land managers, mining industries, universities, and political jurisdictions at all levels.

Although the SEAM Program was assigned to the Intermountain Station, some of its research projects were administered by the Rocky Mountain and Pacific Southwest Research Stations.

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# THE ROLE AND USE OF FIRE IN SAGEBRUSH-GRASS AND PINYON-JUNIPER PLANT COMMUNITIES

## A STATE-OF-THE-ART REVIEW

HENRY A. WRIGHT, LEON F. NEUENSCHWANDER,
AND CARLTON M. BRITTON

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USDA Forest Service General Technical Report INT-58
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION

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# THE ROLE AND USE OF FIRE IN SAGEBRUSH-GRASS AND PINYON-JUNIPER PLANT COMMUNITIES

## A STATE-OF-THE-ART REVIEW

Henry A. Wright,
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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

# FOREWORD

Fire management is a term often used to indicate a broadened perspective of the control and use of fire to meet land management objectives. Barney (1975) defined fire management as "the integrating of fire-related biological, ecological, physical, and technological information into land management to meet desired objectives." One of the most fruitful areas within which to practice these concepts is in that part of our wildlands used for range and wildlife purposes. This paper provides a knowledge base on the role and use of fire in sagebrush-grass and pinyon-juniper plant communities.

Sagebrush-grass and pinyon-juniper plant communities cover several hundred million acres of our western wildlands. The two communities provide the land base for much of the grazing and wildlife habitat in western North America and are increasingly important for recreational pursuits. The authors have drawn upon fire literature, unpublished information, and their own experience to provide this state-of-the-art summary of fire in these plant communities in direct response to the needs of land managers. The Fire in Multiple-Use Research, Development, and Application (RD&A) Program has been interested in preparing state-of-the-art summaries in many vegetative communities to facilitate the integration of fire into land management planning and has cooperated with the authors and their institutions in preparing this paper.

The Bureau of Land Management has been particularly interested in this document and has been helpful in providing the manager's viewpoint. James M. Linne, Bureau of Land Management Research Coordinator attached to the RD&A Program, has utilized this material in preparing prescribed burning guides for BLM field personnel. The findings and recommendations are currently being evaluated and implemented in the field. Thus the information is being utilized concurrently with publication.

The interest of BLM in the use of fire in sagebrush-grass and pinyon-juniper is understandable. Costs of fire suppression are increasing every year. Mechanical means of preparing seedbeds in these vegetation types is expensive. Spraying with herbicides is expensive as well as environmentally controversial. Fire can be used economically and yet be ecologically sound, although, intially, fire may need to be used in combination with other range improvement methods. Other agencies have similar concerns.

New and revised policies in fire management and land management planning call for more definitive answers, particularly in predicting consequences of management activities. This paper provides the basis for incorporating fire into sagebrush-grass and pinyon-juniper communities. It is the first of several state-of-the-art summaries that land managers need for planning the protection and use of fire in different vegetative types. I consider the effort put forth by the authors as a significant contribution to the management of sagebrush-grass and pinyon-juniper communities and to the fire literature.

JAMES E. LOTAN
Program Manager, Fire in Multiple Use
Research, Development, and Application Program

# RESEARCH SUMMARY

Fire frequencies averaged 32 to 70 years in sagebrush-grass communities. Early spring and late fall fires are the least harmful to perennial grasses, although small plants and those with coarse stems are more tolerant of fire than large plants and those with leafy stems. Cheatgrass can be suppressed by burning in early summer, but the set-back is only temporary and perennials such as Idaho fescue and *Stipa* sp. are easily killed during this season of the year. Most forbs can easily tolerate fall burns, but not much data are available for early spring burns. The three subspecies of big sagebrush are easily suppressed by fire. They may or may not become re-established quickly after fire, depending on seed source. Antelope bitterbrush is very susceptible to fire, but some genotypes resprout if moisture is adequate following a burn. Rabbitbrush and horsebrush resprout vigorously after fire. All known data on the effects of fire on plants are summarized in this report.

Drought, competition, and fire played a complementary role in limiting the distribution of pinyon and juniper before grazing by domestic livestock became an influence. Natural fires occurred every 10 to 30 years, which kept the junipers restricted to shallow, rocky soils and rough topography. Heavy livestock grazing has reduced fuel for fires and has permitted pinyon and juniper to rapidly invade adjacent communities. Pinyon and juniper trees less than 1.2 m tall can easily be killed where there is adequate fine fuel to carry a fire, but dense stands of pinyon and juniper with bare soil may require an initial, expensive renovation procedure involving mechanical treatment, prescribed burning, and seeding. Thereafter, however, young pinyon and juniper trees can be kept out of the grassland or sagebrush-grass with a maintenance fire every 20 to 30 years. Mixtures of sagebrush and pinyon-juniper can be easily burned without fine fuel on the ground. Only alligator juniper is a sprouting species.

Effects of fire on grasses, forbs, and shrubs are covered in detail. Guidelines for conducting prescribed burns in sagebrush-grass and pinyon-juniper communities are presented. The guidelines should be used with the understanding that further research is needed to refine all prescriptions.

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# ERRATA

Wright, Henry A., Leon F. Neuenschwander, and Carlton M. Britton. 1979. The role and use of fire in sagebrush-grass and pinyon-juniper plant communities. USDA For. Serv. Gen. Tech. Rep. INT-58, 48 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Page 9, next to last paragraph:

Sentence beginning in third line of paragraph should read:

"Fire will not convert pure stands of cheatgrass to native perennials."

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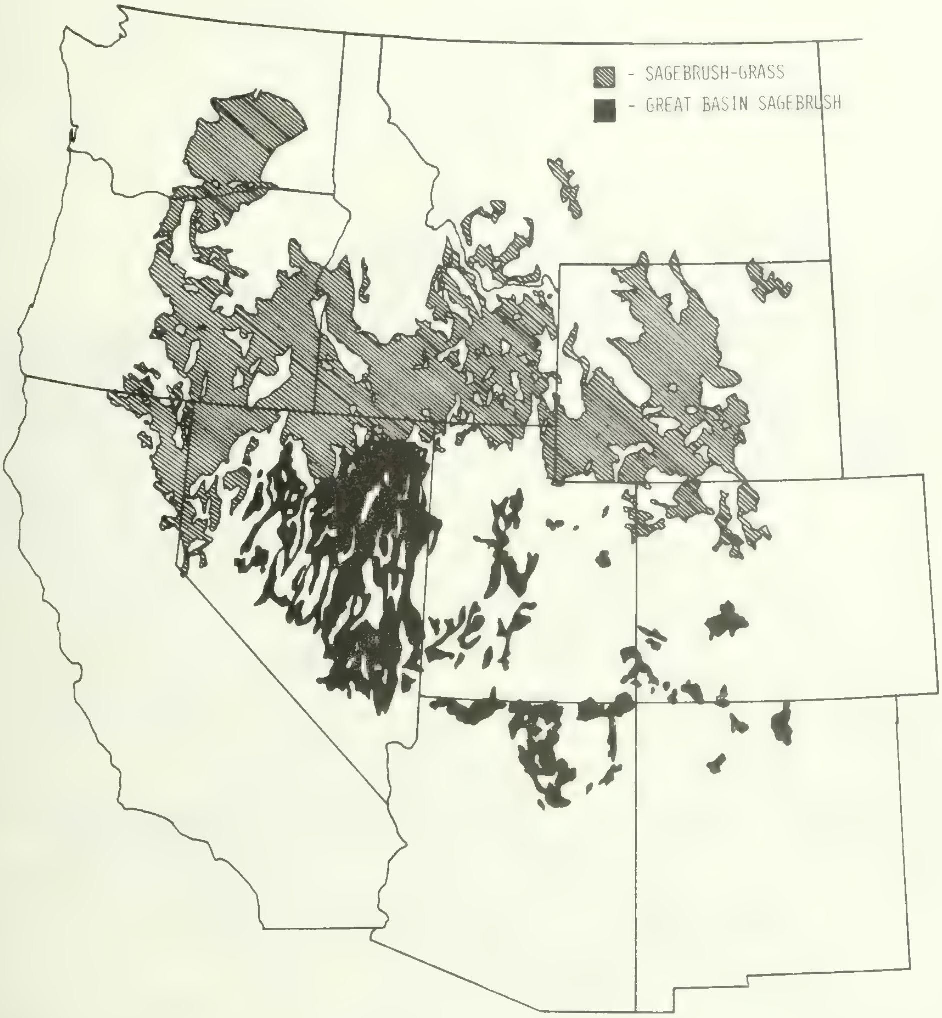
# SAGEBRUSH-GRASS COMMUNITIES

## Distribution, Climate, Soils, and Vegetation

Sagebrush-grass vegetation covers at least 96.5 million acres (39.1 million ctares) in the Western United States (USDA Forest Service 1936), but probably consid-ably less than the 270 million acres (109 million hectares) estimated by Beetle in 60 (Tisdale and others 1969). The largest contiguous area lies in eastern Oregon, uthern Idaho, southwestern Wyoming, northern Utah, and northern Nevada (Vale 1975). st of this area (fig. 1) occurs below the pinyon-juniper zone, but in the absence of pinyon-juniper zone, sagebrush-grass vegetation will border curlleaf mahogany *ercocarpus ledifolius*), Gambel oak (*Quercus gambelii*), ponderosa pine (*Pinus ponderosa*) Douglas-fir (*Pseudotsuga menziesii*). Sagebrush-grass communities also occur above e pinyon-juniper zone in the Great Basin (Billings 1951) and throughout most mountain ant communities in the Rocky Mountain and Intermountain regions (Beetle 1960).



*gure 1.--Distribution of sagebrush and sagebrush-grass communities in the Western United States after Küchler (1964).*

Most of the sagebrush-grass zone is found at elevations from 2,000 to 7,000 ft (610 to 2,134 m). The sagebrush-grass zone also occurs below 1,000 ft (305 m) in south central Washington and British Columbia and mixes with all vegetation zones to varying degrees up to 10,000 ft (3,049 m) (Beetle 1960), including the subalpine herbland. Where sagebrush-grass prevails below 7,000 ft (2,134 m), annual precipitat varies between 8 to 20 inches (20 to 50 cm) (Tisdale and others 1969). Soil texture varies from loamy sand to clay (Tisdale and others 1969). Most soils are derived fr basalt, although extensive areas have soils derived from rhyolite (southeastern Oreg and Nevada), loess, lacustrine, alluvium, and limestone. Interactions of soils, precipitation, and elevation results in many distinct combinations of sagebrush-gras dominated ecosystems.

Three subspecies of big sagebrush--basin big sagebrush (*Artemisia tridentata* ss *tridentata*), Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*), and mou tain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*)--dominate the sagebrush-gras Basin big sagebrush (3.28 to 16.41 ft; 1 to 5 m tall) and Wyoming big sagebrush (1.4 to 2.43 ft; 0.45 to 0.76 m tall) are the dominants from 2,001 to 7,002 ft (610 to 2,134 m), with the latter being the most drought tolerant (McArthur and others 1974) Basin big sagebrush occupies a 10- to 16-inch (25 to 40 cm) precipitation zone on deep, well-drained alluvial soils, whereas Wyoming big sagebrush occupies an 8- to 1 inch (20- to 30-cm) precipitation zone on shallow soils (Tisdale and others 1969). Mountain big sagebrush (2.43 to 4.00 ft; 0.76 to 1.22 m tall) is the most mesic subspecies and can be found at elevations from 5,000 to 10,000 ft (1,524 to 3,049 m) (McArthur and others 1974) where precipitation varies from 14 to 20 inches (35 to 50 per year (fig. 2).

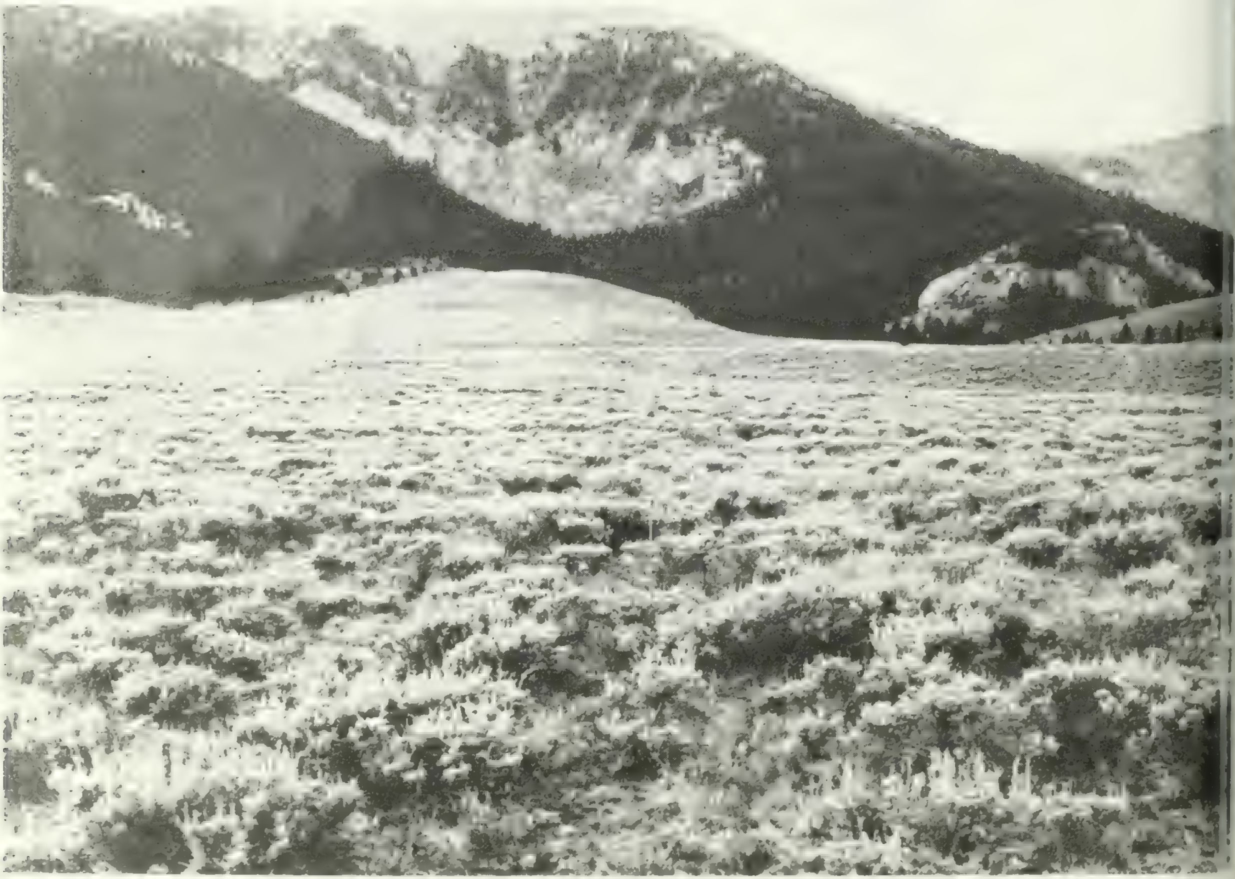


*Figure 2.--Mountain big sagebrush in Idaho with an understory of Idaho fescue. (Univ sity of Idaho photo.)*

Other species of sagebrush, in decreasing order of economic importance, are low gebrush (*A. arbuscula*), three-tip sagebrush (*A. tripartita*), black sagebrush (*A. nova*), lver sagebrush (*A. cana* ssp. *viscidula* and *A. cana* ssp. *bolanderii*), alkali sagebrush . *longiloba*), Bigelow sagebrush (*A. bigelovii*), and scabland sagebrush (*A. rigida*) isdale and others 1969; McArthur and others 1974). The first three species generally ow below 6,000 ft (1,830 m) elevation, although they can occur at higher elevations. w sagebrush occurs on shallow soils or soils with a restrictive B horizon, largely in uthern Idaho, Nevada, southeastern Oregon, and northeastern California (Fosberg and ronaka 1964). Three-tip sagebrush occurs east of this region on mesic or dry soils a precipitation zone of 10 to 16 inches (25 to 40 cm). Black sagebrush is usually sociated with calcareous soils on dry sites, but can occur on mesic sites of the uglas-fir zone in eastern Idaho. Silver sagebrush occurs primarily in spring-flooded ttomlands, and at high elevations where snow drifts. All species except three-tip gebrush and silver sagebrush are nonsprouters. Three-tip sagebrush is a weak sprouter, lver sagebrush, a vigorous sprouter.

Major shrubs associated with big sagebrush include antelope bitterbrush (*Purshia identata*), horsebrushes (*Tetradymia* ssp.), rabbitbrush (*Chrysothamnus* sp.), and broom akeweed (*Xanthocephalum sarothrae*). Spiny hopsage (*Grayia spinosa*) and mormon tea *hedra nevadensis*) are sporadically present in the lower rainfall areas near the Salt sert.

Dominant grasses include bluebunch wheatgrass (*Agropyron spicatum*), Idaho fescue *estuca idahoensis*), needle-and-thread (*Stipa comata*), Thurber needlegrass (*Stipa urberiana*), and to a lesser extent Indian ricegrass (*Oryzopsis hymenoides*). All of ese species or only one may be present in a particular understory. Needle-and-thread d Indian ricegrass dominate sandy soils throughout the sagebrush-grass zone. On other ils, bluebunch wheatgrass dominates areas with moderate annual precipitation [9 to inches (22 to 35 cm)] and Idaho fescue dominates the most mesic sites, generally ose with more than 14 inches (35 cm) of annual precipitation. Temperature interacts h precipitation, so the moisture threshold that separates bluebunch wheatgrass from aho fescue can vary from 12 to 16 inches (30 to 40 cm) of precipitation annually. urber needlegrass occurs on medium-textured soils in an 8- to 12-inch (20- to 30-cm) ecipitation zone. Sandberg bluegrass (*Poa sandbergii*) and bottlebrush squirreltail *tanion hystrix*) are the most common subdominant bunchgrasses. Junegrass (*Koeleria stata*) and other *Poa* spp. are also often present if the annual precipitation is ove 11 inches (28 cm). Rhizomatous grasses that occupy localized areas include ckspike wheatgrass (*Agropyron dasystachyum*), plains reedgrass (*Calamagrostis tanensis*), and riparian wheatgrass (*Agropyron riparium*). Cheatgrass (*Bromus torum*), an introduced annual, occupies millions of acres on disturbed ranges emmedson and Smith 1964). Medusahead (*Taeniatherum asperum*), another introduced ual, occupies disturbed clay sites that have well-developed profiles (Dahl 1966).

Forbs are present in great variety and abundance in climax communities where the cipitation is in excess of 11 to 12 inches (28 to 30 cm) per year. They may count for as much as 50 percent of the herbaceous production in eastern Idaho. For s reason herbicides, at least in our opinion, are undesirable to manage sagebrush-ss communities in eastern Idaho where balsamroot (*Balsamorhiza sagittata*) and ine (*Lupinus* sp.) are typically the most abundant forbs. Forbs account for only o 15 percent of the herbaceous vegetation in eastern Oregon. Groundsel (*Senecio* ), tapertip hawksbeard (*Crepis acuminata*), western yarrow (*Achillea millefolium*), locoweed (*Astragalus* sp.) are the most common forbs and recover within 3 to 4 rs after the use of herbicides (Sneva 1977, personal communication)[1].

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[1] Listed under unpublished references.

## Fire History

Before the influence of man, fire covered contiguous units of sagebrush-grass communities in northern Yellowstone National Park at an average frequency of 32 to 70 years (Houston 1973). Within a large portion of this locale, however, fire swept sma areas at least every 17 to 41 years. Dating all fires that occurred within a locale, Houston theorized that the frequency of fire in sagebrush communities within Yellowst Park was 20 to 25 years. This estimated frequency was based on the assumption that t record of fire scars for any one tree underestimated the frequency of fire because no all trees were scarred by every fire. Houston's findings that many but not all trees had fire scars with similar dates suggests that once burned, an area was unlikely to have sufficient fuel to reburn for several years.

Based on the vigorous response of horsebrush (*Tetradymia canescens*) to fire and 30-plus years that are needed for it to decline to a low level after a fire (Harniss Murray 1973), probable frequency of fire would be about 50 years. If fires occurred every 20 to 25 years, as Houston implies, many sagebrush-grass communities could be dominated by horsebrush and rabbitbrush.

## Ecological Effects of Fire

### *Grasses and Forbs*

The effect of fire on grasses depends largely on growth form and season of burni Bunchgrasses with densely clustered culms, such as Idaho fescue and needle-and-thread can be severely harmed by fire (Blaisdell 1953; Wright 1971), especially if burned du June or July (Wright 1971). Their dense culms will burn 2 to 3 hours after a fire passes. Temperatures as high as 1,000°F (538°C) will be reached 45 min after a fire has passed (Wright 1971). Thus, many plants often die or have only a few culms that survive, regardless of the intensity of the passing fire. Late summer and fall burns are the least harmful.

Threadleaf sedge (*Carex filifolia*) also has a compact growth form and is severel harmed by fire (Vallentine 1971). Idaho fescue is very senstitive to summer and fall fires where the precipitation is marginal for its existence (Blaisdell 1953; Conrad and Poulton 1966). Preliminary research in eastern Oregon indicates that Idaho fesc will recover in 2 to 3 years if burned when the soil is moist in early spring (Britt and Sneva 1977, personal communication; Caraher 1977, personal communication).

Bluebunch wheatgrass; bottlebrush squirreltail, and the crested wheatgrasses (*Agropyron cristatum*, *A. desertorum*, and *A. sibericum*) are less susceptible to fire injury than Idaho fescue or *Stipa* sp. (Blaisdell 1953; Conrad and Poulton 1966; Wrigh 1971; Vallentine 1971) because the former are mostly coarse stems with a minimum of leafy material. They burn quickly and little heat transfers below the soil surface (Wright 1971). Moreover, the small size of Sandberg bluegrass and bottlebrush squir tail in climax communities helps them survive fires (Wright and Klemmedson 1965); therefore they usually increase in abundance after a fire. All rhizomatous grasses such as thickspike wheatgrass and plains reedgrass increase immediately after a fire (fig. 3) (Blaisdell 1953). Production from rhizomatous grasses on burned plots will above that on controls for about 30 years (Harniss and Murray 1973).

*igure 3.--Dense stand of thickspike wheatgrass and plains reedgrass 3 years after burning a mountain big sagebrush community near Dubois, Idaho. Patches of sagebrush in the background were not burned by the fire.*

Bluebunch wheatgrass will return to preburn production in 1 to 3 years (fig. 4) Blaisdell 1953; Moomaw 1957; Conrad and Poulton 1966; Uresk and others 1976; Daubenmire 963, unpublished progress report); needle-and-thread in 3 to 8 years, depending on ite (Blaisdell 1953; Dix 1960; Wright 1977, unpublished observation); and Idaho fescue n 2 to 12 or more years, depending on soil moisture, season, and intensity of the ire (Blaisdell 1953; Conrad and Poulton 1966; Harniss and Murray 1973; Britton and neva 1977, personal communication). The response of prairie junegrass (*Koeleria ristata*) to fire is similar to that of needle-and-thread (Vallentine 1971). Cusick luegrass (*Poa cusickii*) is reduced 50 percent the first growing season after burning Uresk and others 1976). Indian ricegrass (*Oryzopsis hymenoides*) is only slightly amaged by fire (Vallentine 1971).

Repeated burning every few years or burning in early summer will deplete a stand f perennial grasses and allow annual grasses, chiefly, cheatgrass (*Bromus tectorum*), o increase sharply (Pickford 1932; Wright and Klemmedson 1965). Once a sagebrush-rass community is depleted of perennial plant cover, secondary succession goes from ussian thistle (*Salsola kali*) to mustard (*Sisymbrium* and *Descurainia* sp.) to cheatgrass within 5 years (Piemeisel 1951). Pechanec and Hull (1945) found that burning ear Boise, Idaho, reduced cheatgrass plants in varying numbers, depending on the month f the burn, as follows:

| Burn | Cheatgrass plants | |
|---|---|---|
| Month | (ft$^2$) | (m$^2$) |
| June | 14 | 15 |
| July | 11 | 12 |
| August | 41 | 44 |
| October | 45 | 48 |
| November | 124 | 133 |

The early summer burns are only a temporary setback for cheatgrass at a time of the year when climax perennials are easily killed by fire (Wright and Klemmedson 1965). Hence, the density of cheatgrass increases over time while fewer perennials survive after each fire.

Such areas can only be reclaimed by chemical fallow techniques (Eckert and Evan 1967) or plowing and then seeding. Most seeding has been done with wheatgrass (Hull 1971). Fairway wheatgrass (*Agropyron cristatum*), crested wheatgrass (*A. desertorum*) and Siberian wheatgrass (*A. sibericum*) are well adapted to this zone. Fairway wheatgrass is best adapted to moderately mesic sites and Siberian wheatgrass is best adap to the driest sites in the 8- to 12-inch (20- to 30-cm) precipitation zone.

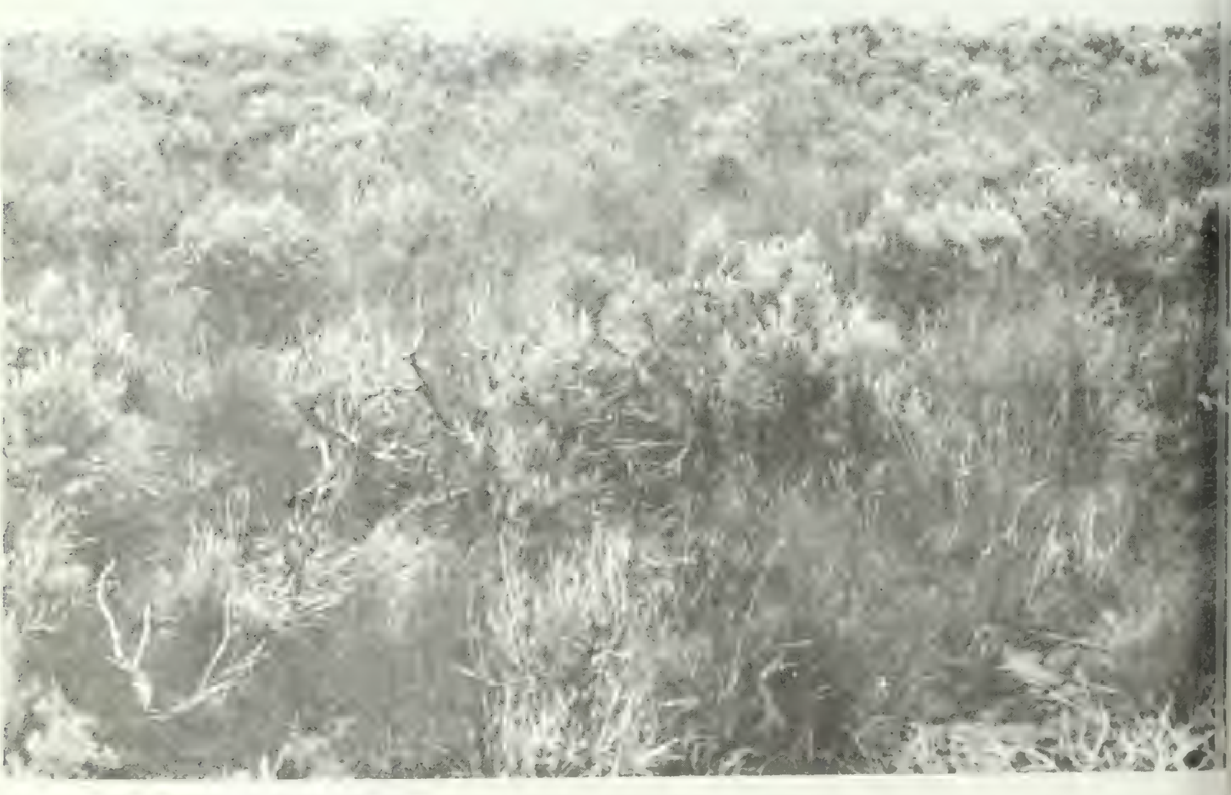

*Figure 4.--Excellent stand bluebunch wheatgrass with a moderate amount of Basin big sagebrush in Idaho. Sagebrush communities like this one do not impede animal move and do not need to be burned. (University of Idaho photo.)*

Fall burning does not harm most forbs because many of them are dry and often isintegrated by this time. However, some forbs remain green and are very susceptible o fire. Pechanec and others (1954) classified forbs according to their susceptibility o fire (table 1). Unpublished data in Utah show that late summer or fall burning an kill Indian paintbrush (*Castilleja angustifolia*) (Frischknecht 1977, personal comunication).

ble 1.--*Susceptibility of forbs to fire by three damaged classifications at Dubois, Idaho (Pechanec and others 1954)*

| Severely damaged | Slightly damaged | Undamaged |
|---|---|---|
| *tennaria dimorpha* | *Astragalus* sp. | *Achillea lanulosa* |
| *tennaria microphylla* | *Castilleja angustifolia* | *Allium* sp. |
| *enaria uintahensis* | *Crepis acuminata* | *Arnica fulgens* |
| *igeron engelmannii* | *Geranium viscocissimum* | *Balsamorhiza sagittata* |
| *iogonum caespitosum* | *Lupinus caudatus* | *Comandra umbellata* |
| *iogonum heracleoides* | *Penstemon radicosus* | *Erigeron corymbosus* |
| *lox canescens* | *Sphaeralcea munroana* | *Lupinus leucophyllus* |
| | | *Phlox longifolia* |
| | | *Senecio integerrimus* |
| | | *Sisymbrium linifolium* |
| | | *Zygadenus paniculatus* |

After 12 years, Blaisdell (1953) found that only the heavy sagebrush-grass burn ll sagebrush plants consumed by fire) supported more forbs than the control 12 years ter burning. By the end of 30 years, forbs had returned to preburn levels (Harniss d Murray 1973), although both burned and unburned plots contained at least 5 times many forbs as before the burn.

### *rubs*

Fires can have a devastating and long-lasting effect on shrubs in sagebrush-grass mmunities. Big sagebrush, a nonsprouter, is highly susceptible to fire injury (ickford 1932; Blaisdell 1953). Blaisdell found that the production of this species burned areas in Idaho was only 10 percent of that on the control 12 years after the rn, but was near preburn levels 30 years after the burn (Harniss and Murray 1973). Some areas, however, recover much more quickly. Differences in recovery rates may be lated to season of burn as it affects seed production (Johnson and Payne 1968), summer precipitation, and completeness of burn. Three-tip sagebrush is also damaged fire, but some plants resprout (Blaisdell 1953).

Antelope bitterbrush is severely damaged by burning (fig. 5) (Blaisdell 1953; Pechanec and others 1954; Countryman and Cornelius 1957; Nord 1965). In Idaho 12 to years after an experimental burn, antelope bitterbrush was still producing only 50 60 percent as much as the control (Blaisdell 1953). If soil is wet at the time of burning or shortly after the burn, antelope bitterbrush regularly resprouts (Blaisdell 53; Blaisdell and Mueggler 1956; Nord 1965). If the plants resprout, they will regain original growth in 9 to 10 years (Blaisdell 1953). Where fires are not followed by rain, antelope bitterbrush seldom sprouts. In southern California, however, desert bitterbrush (*P. glandulosa*) resprouts vigorously and abundantly (Nord 1965) even without postfire rains.

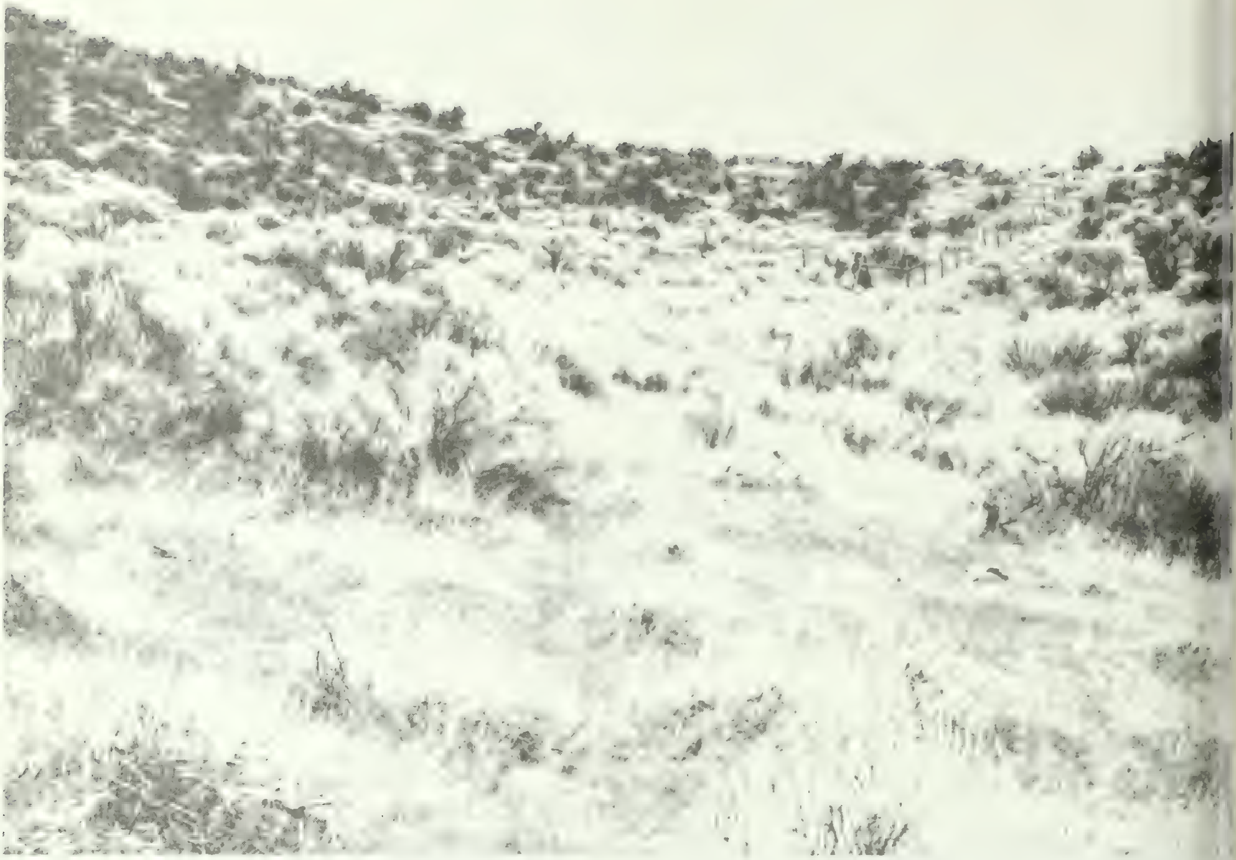

*Figure 5.--When bitterbrush (dark plants) is a major component of a plant community, burning should be carefully planned. Bitterbrush is easily damaged by fire and should either be protected from fire or burned when the soil is wet. Photo taken near Boise, Idaho.*

Other species severely damaged by fire include cliffrose (*Cowania mexicana*), cu leaf mountain-mahogany (*Cercocarpus ledifolius*), granite gilia (*Gilia pungens*), and broom snakeweed (*Xanthocephalum sarothrae*) (Pechanec and others 1954; Vallentine 197 Curlleaf mountain-mahogany is a weak sprouter (Monsen 1977 personal communication). Burning damages mountain snowberry (*Symphoricarpos orephilus*), but yield remains undamaged 15 years after burning (Pechanec and others 1954; Blaisdell 1953). Oregon grape (*Mahonia repens*) is favored by burning, especially after intense fires (Blaisd 1953).

Rabbitbrush (*Chrysothamnus* sp.), a common genus in the sagebrush-grass zone, is usually enhanced by fire (Cottam and Stewart 1940; Blaisdell 1953; McKell and Chilco 1957; Countryman and Cornelius 1957, Chadwick and Dalke 1965; Young and Evans 1974). An exception to this general response is apparent in rubber rabbitbrush (*Chrysothamn nauseosus*). Robertson and Cords (1957) reported no recovery of this species 2 years after a burn on September 3, 1942, near Mono Lake, Calif., and after a burn on Novem 7, 1943, near McGill, Nev. However, burning in the latter area was repeated on an unburned area the following year on the same date and 95 percent of the plants respr Evidently, the intensity of the fire is important because most of the sprouting afte fire is epicormic (stem sprouting), not basal or root sprouting (Monsen 1977, person communication).

*Chrysothamnus viscidiflorus* (all of its varieties and subspecies) resprouts gorously. Generally, production is reduced for 1 to 3 years after burning, then it reases dramatically. On the U.S. Sheep Station near Dubois, Idaho, burning reduced duction 59 percent the first year after burning (Blaisdell 1953). Three years after ning, production had doubled and was tripled at the end of 12 years (Blaisdell 3). Similarly, Chadwick and Dalke (1965) found that the cover of *C. viscidiflorus* increased 4 to 9 times on 8- to 18-year-old burns on sandy soils in northeast ho. Production of *C. bloomeri* (*C. viscidiflorus*) doubled 5 years after a burn in thern California (Countryman and Cornelius 1957). In western Nevada, Young and ns (1974) found that green rabbitbrush (*C. viscidiflorus* var. *viscidiflorus*) continued dominate burns and re-establish itself periodically for 15 years. Communities 40 50 years old were dominated by big sagebrush and contained reduced populations of en rabbitbrush.

Production of horsebrush (*Tetradymia canescens*) was reduced about 50 percent the st year after burning, but doubled at the end of 3 years (Blaisdell 1953). At the of 12 years it had increased fivefold. After 30 years, many of these plants were ng out, but production was still 60 percent above that in the unburned control rniss and Murray 1973). Fire greatly enhances the dominance of this species.

Desirable shrubs such as serviceberry (*Amelanchier alnifolia*), snowbrush ceanothus *anothus velutinus*), and true mountain-mahogany (*Cerocarpos montanus*) are not damaged fire (Vallentine 1971).

## Management Implications

Prescribed fire can be a useful tool in many big sagebrush communities if the es are carefully planned and livestock do not graze the burn for two growing seasons. oval of tall, thick sagebrush by fire will greatly enhance movement of livestock will release grasses and forbs from competition, resulting in increased yields. ever, depending on the vegetation, fires should not be too frequent and should be nned in early spring or after late summer. Caution should be exercised where elope bitterbrush is dominant and where horsebrush or rabbitbrush are abundant. re forbs are abundant or sagebrush is tall and thick, fall burning may be preferred r chemical treatments as a management tool (figs. 6,7).

In the sagebrush-grass region, much burning can be done without firelines, ecially where patches of big sagebrush grow in swales or in small ravines surrounded low sagebrush. Fires will not carry in low sagebrush, even when winds are 20 mi/h km/h). This condition is highly desirable because only big sagebrush growing on the t productive sites is burned and such burning creates an ideal mosaic for wildlife. ilarly, early spring burning can be done at higher elevations in pure stands of sagebrush where snow patches can be used as firelines. Reduction of big sagebrush, not low sagebrush, is desirable for game management. Livestock should be prevented m concentrating on the burned areas.

Burning followed by seeding will suppress medusahead, but the practice is not very cessful where cheatgrass is dominant. Most cheatgrass areas must be treated with micals or plowed and then seeded if perennials are desired. Fire will convert pure nds of cheatgrass to native perennials. Likewise, pure stands of cheatgrass will revert to native perennials with rest. Such areas have a high fire frequency and 1 decline in site potential (Young and others 1976).

Areas that are primarily sagebrush and cheatgrass can be successfully seeded after e if the burns are hot enough to consume the sagebrush plants (Young and others 1976), at the same time destroy cheatgrass seed. If much live cheatgrass seed remains, the n should be chemically fallowed (Eckert and Evans 1967), or the germinating cheat- ss plowed before drilling with perennial wheatgrasses.

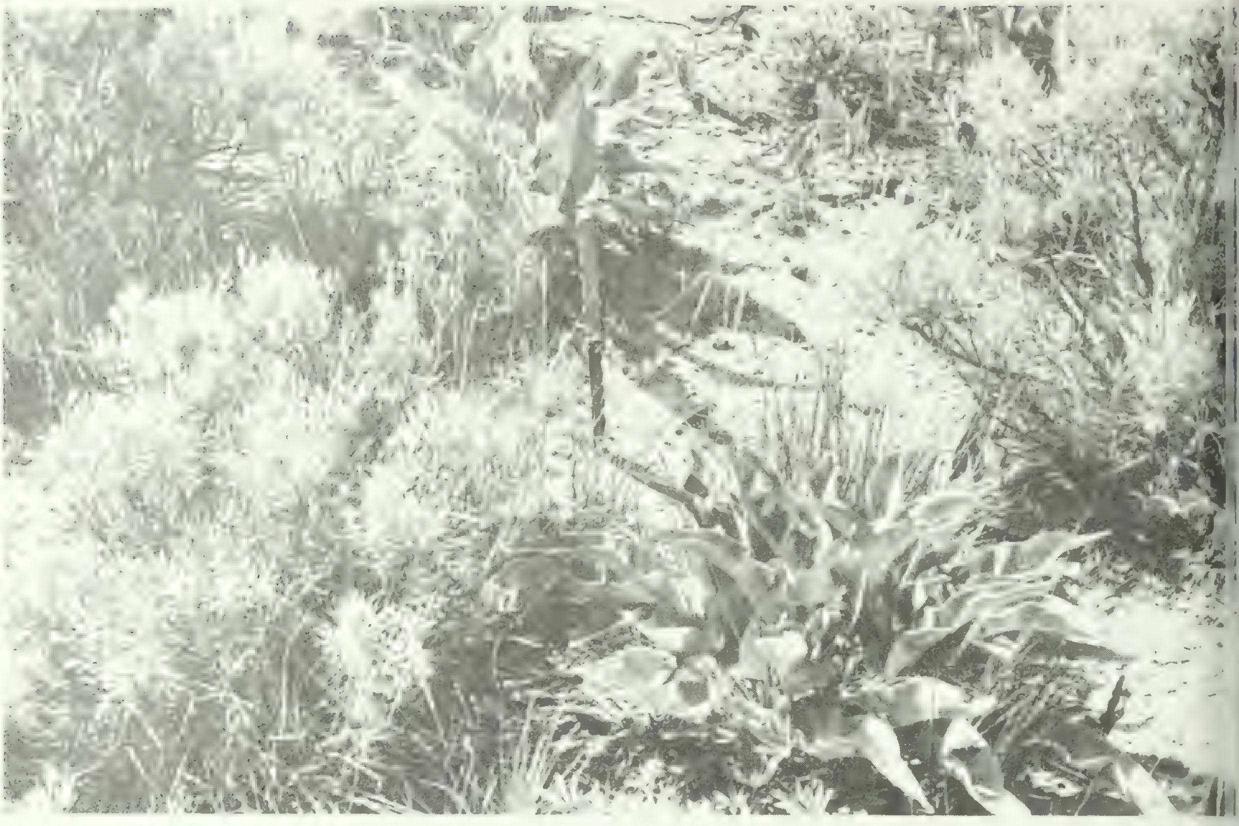

Figure 6.--Balsamroot and lupine make up a large component of the herbaceous yield i
this three-tip sagebrush community. Fall burning would help to maintain the forb
component.

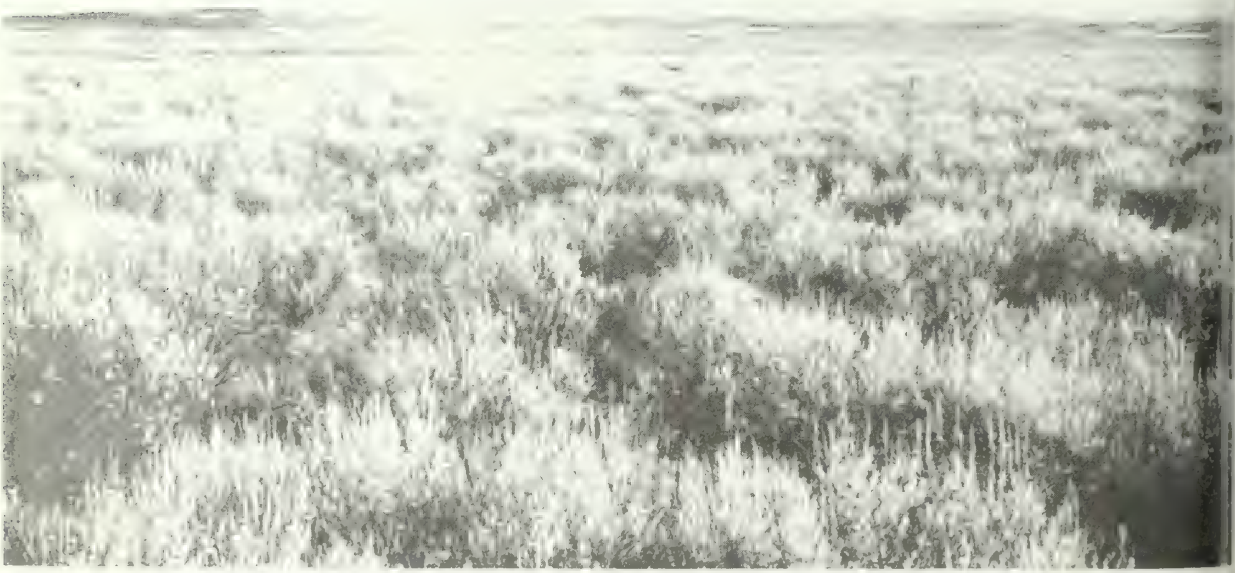

Figure 7.--Dense stands of Basin big sagebrush suppress the yeild of herbaceous spec
and impede livestock movements. Fire would create variety in the habitat and enha
forbs and grasses. Photo taken in southern Idaho.

## State-of-the-Art

We know generally how most shrubs and herbaceous species respond to fire in sagebrush-grass communities, but more information is needed on bluebunch wheatgrass, Idaho fescue, the big sagebrush subspecies, and bitterbrush. Fire intensity, season of urn, plant size, and soil moisture should be evaluated for several years at a variety f locations for bluebunch wheatgrass and Idaho fescue. More long-term fire effects ata are badly needed for Idaho fescue.

Big sagebrush subspecies will sometimes invade burned areas rapidly and sometimes ery slowly. McDonough and Harniss (1974) have studied the germination requirements f big sagebrush but more studies are needed. Timing of burns in relation to seed aturity, residual seed supply in soil after various intensities of heat, and response f sagebrush seed to soil moisture over a period of years all need to be evaluated. agebrush seed dispersal has been studied by Frischknecht (1962). He found that the ean maximum spread distance of big sagebrush seed was 42 ft (13 m) from parent plants.

We also need more research comparing spring and fall burns. Where forbs are not mportant in plant communities, early spring burning appears to be more favorable for unchgrasses than late summer or fall burns.

Prescription data for sagebrush-grass burns have been given by Pechanec and others 1954) and more recently by Ralphs and others (1976). Nevertheless, the data needs to e strengthened. Proper fireline width is still unknown, and the potential for spot-ires in sagebrush-grass communities needs to be more thoroughly documented, although agebrush is less volatile (Powell 1970) than chamise and pinyon-juniper.

# PINYON-JUNIPER COMMUNITIES

## Distribution, Climate, Soils, and Vegetation

The pinyon-juniper association covers from 43 to 76 million acres (17.4 to 30.8 illion hectares) in Western North America, depending on whether you use Küchler's 1964) map (fig. 8) of potential pinyon-juniper woodland (the lower figure) or the arlier Senate Document 199 (Clapp 1936) wherein all western lands then having juniper, ith or without pinyon pines, were included. West and others (1975) have taken a iberal definition of pinyon-juniper woodlands and included both Küchler's "juniper-inyon woodlands" and "juniper steppe" types, plus the areas within the Great Basin agebrush, sagebrush-grass steppe, and the Trans-Pecos shrub savannah where junipers re abundant. Leaving out the juniper woodlands in Texas, the figure by West and thers (1975) for the Western United States is 75 million acres (30.4 million hectares). xcept for the Central Great Basin where pinyon and juniper appear to be superimposed pon a large *Artemisia*/cool-season grass zone (Billings 1951), pinyon-juniper woodlands re located below the Gambel oak (*Quercus gambelii*) and ponderosa pine (*Pinus ponderosa*) ones, but above the sagebrush (*Artemisia* sp.) or grassland areas into which juniper, he least mesic of the two dominants, is continually spreading.

Pinyon-juniper woodlands extend from the east slope of the Sierra Nevada, eastward hroughout the mountains of the Great Basin in Nevada and Utah, and on both flanks of he Rocky Mountains in Colorado (as well as mesas of the Colorado Plateau and interior alleys), then southward into Arizona, New Mexico, and northern Mexico (West and others 975). Dense stands of juniper alone that join the pinyon-juniper woodlands extend urther north into eastern Oregon, southern Idaho, and Wyoming.

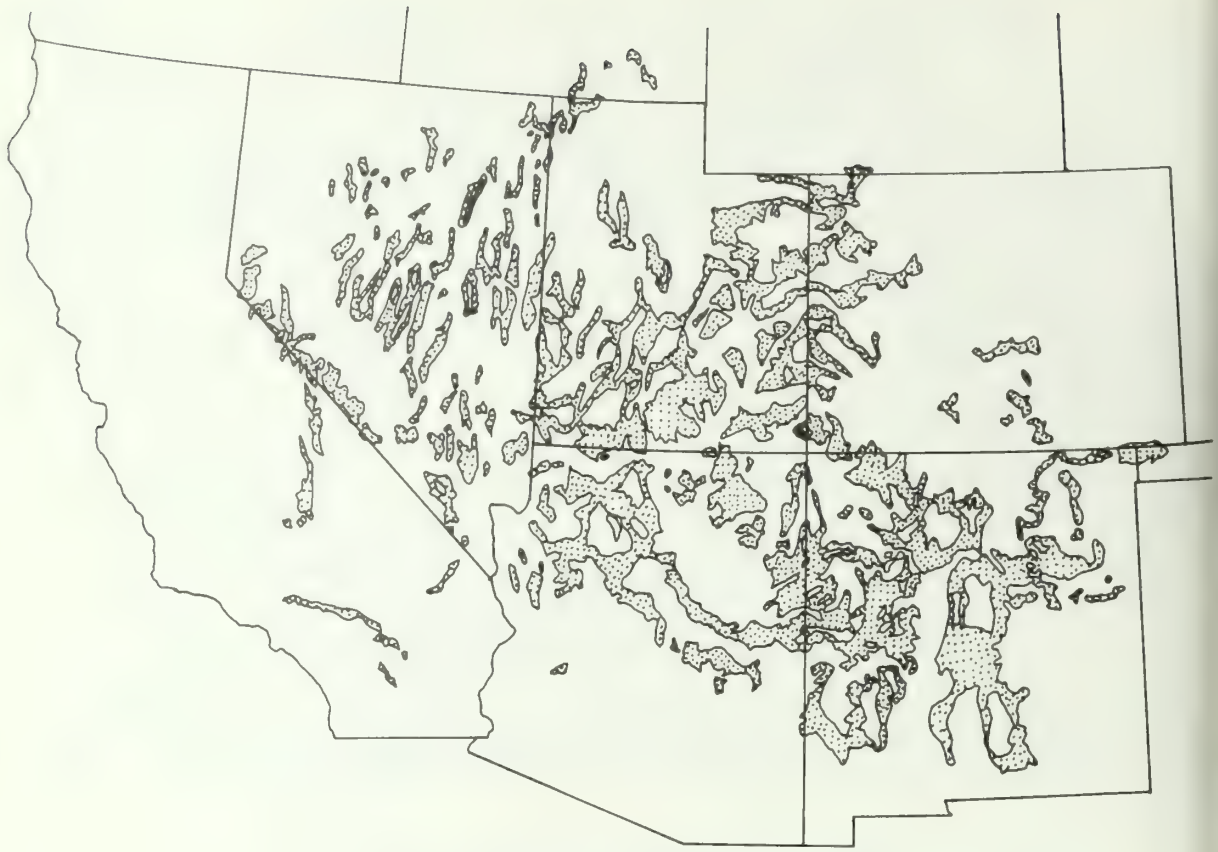

*Figure 8.--Distribution of pinyon-juniper woodlands in the southeastern United States after Küchler (1964).*

Pinyon-juniper woodlands are generally found at elevations from 4,500 to 7,500 ft (1,372 to 2,287 m) (Springfield 1976), but they are best developed between 5,000 and 7,000 ft (1,524 to 2,134 m) (Woodbury 1947). Nevertheless, pinyon-juniper may be found growing from 2,500 to 3,000 ft (762 to 915 m) in the upper parts of deserts (Johnsen 1962; Franklin and Dyrness 1969) to 9,000 ft (2,744 m) in ponderosa pine forests (Lanner 1975). The highest elevation for pinyon-juniper woodland is nearly 10,000 ft (3,049 m) in the White Mountains of California, where the Sierra Nevada create an extreme rain-shadow effect (St Andre and others 1965). The upper altitudinal limit of the pinyon-juniper zone is determined by low temperature, and the lower range by a deficiency in moisture (Pearson 1920; Daubenmire 1947).

Annual precipitation varies from 10 to 15 inches (25 to 38 cm) over most of the pinyon-juniper zone where stands are open (fig. 9) (Woodbury 1947), but dense stands may receive 16 to 22 inches (40 to 55 cm) of rain and snow (Springfield 1976). On xeric sites at high elevations, annual precipitation of pinyon-juniper communities may be as high as 26 inches (65 cm) (Pearson 1931). Pinyon (*Pinus edulis* and *P. monophylla* is usually most abundant at the higher elevations of the pinyon-juniper zone, with a mixing of pinyon and juniper at midelevations (Reveal 1944; West and others 1975; Springfield 1976). Because pinyon is very susceptable to fire damage (Leopold 1924), as well as being the more moisture-demanding of the two genera, fire, in addition to lower moisture, probably keeps pinyon out of the lower elevations.

*igure 9.--An open stand of pinyon-juniper with blue grama understory in eastern New Mexico.*

Distribution of the pinyon-juniper association is not limited by parent material Emerson 1932; Springfield 1976) or soil texture (Pearson 1931; Springfield 1976). The rees grow on residual and transported soils derived from sandstones, limestones, basalt, ranite, and mixed alluvium (Springfield 1976). Soil textures vary from stony, cobbly, nd gravelly loams to clay-loam and clay, and in depth from shallow to deep (Springfield 976), but the best stands of pinyon are found on coarse gravel, gravelly loam, or oarse sands (Phillips 1909). The soils are generally calcareous and alkaline, but uniper grows well on acid soils down to a pH of 4.7 (Arend 1950). Except for those oils derived from basalt, most are low in fertility (Howell 1941; Springfield 1976) nd often shallow and rocky.

Dominant tree species of the pinyon-juniper woodlands are Utah juniper (*Juniperus steosperma*), one-seed juniper (*J. monosperma*), Rocky Mountain juniper (*J. scopulorum*), lligator juniper (*J. deppeana*), doubleleaf pinyon (*Pinus edulis*), and singleleaf pinyon *P. monophylla*). Doubleleaf pinyon is associated with the Southern Rocky Mountains and xtends westward to the eastern edge of the Great Basin. Throughout the Great Basin, astern slope of the Sierra Nevada, and western portions of Arizona, singeleaf pinyon s associated primarily with Utah juniper.

Utah juniper is the most important of its genus in the pinyon-juniper woodland anner 1975). Its range extends over northern Arizona, Utah, Nevada, and parts of alifornia. One-seed juniper extends from central Colorado to central Arizona and t is widely distributed throughout most of New Mexico. Some one-seed juniper is ound in the Palo Duro Canyon of West Texas. Alligator juniper, a sprouting species, s also widespread in the Southwest. It is abundant in Mexico and reaches its northern mits in north-central Arizona and New Mexico. Rocky Mountain juniper occurs only at e higher elevations of the pinyon-juniper woodland (Lanner 1975).

Outside of the pinyon-juniper woodland, western juniper (*J. occidentalis*) is ver abundant in eastern Oregon. East of New Mexico, additional species of juniper such a redberry juniper (*J. pinchoti*), a sprouting species, Ashe juniper (*J. ashei*), and eas ern red cedar (*J. virginiana*) are abundant. The latter junipers are usually associat with rocky slopes such as escarpments, ridges, or rimrocks throughout the Great Plain (Wells 1970), and alkaline soils such as the Edwards Plateau in central Texas. From the rocky areas where juniper is considered to be the climax in the Plains, trees hav spread rapidly into the surrounding grasslands in the absence of fire. Eastern red cedar is the most extensive species and occurs from Texas northeastward throughout mo of the Eastern United States.

Herbaceous species vary considerably throughout the pinyon-juniper zone. On the eastern flank of the Rocky Mountains in New Mexico, blue grama (*Bouteloua gracilis*) i the dominant herbaceous understory, with some sideoats grama (*B. curtipendula*) and wolftail (*Lycurus phleoides*) and a few forbs often intermixed (Pieper and others 1971 In north-central Arizona, blue grama and sideoats grama remain as dominant grasses, b prairie junegrass (*Koeleria cristata*), bottlebrush squirreltail (*Sitanion hystrix*), muttongrass (*Poa fendleriana*), and black dropseed (*Sporobolus interruptus*) are import components (Clary 1971). Other sites include desert needlegrass (*Stipa speciosa*) (Thatcher and Hart 1974), red threeawn (*Aristida longiseta*) and ring muhly (*Muhlenber torreyi*) (Jameson and Reid 1965), and western wheatgrass (*Agropyron smithii*) (Clary a Morrison 1973). Forbs and half shrubs make up about 50 percent of the herbaceous composition in north-central Arizona. Broom snakeweed (*Xanthocephalum sarothrae*), sulfur eriogonum (*Eriogonum cognatum*), plumweed birdbeak (*Cordylanthus wrightii*), and goldeneye (*Viguiera* sp.) are dominants (Clary 1971).

Northward, warm-season grasses drop out of the understory. In southwestern Colorado on Mesa Verde National Park, the meadow stage that develops 4 years after burning is dominated by Indian ricegrass (*Oryzopsis hymenoides*), bottlebrush squirrel tail, and muttongrass (Erdman 1970). Forbs and shrubs are also present at various stages of succession after burning. In Utah, bluebunch wheatgrass (*Agropyron spicatu* and western wheatgrass are the most abundant grasses, with lesser amounts of Sandberg bluegrass (*Poa sandbergii*), bottlebrush squirreltail, and Indian ricegrass (Barney an Frischknecht 1974). Forbs are a minor component.

Many sources (Blackburn and others 1969; Jensen 1972; Klebenow and others 1976) indicate that in Nevada common grasses include bottlebrush squirreltail, Sandberg blu grass, needle-and-thread (*Stipa comata*), Great Basin wildrye (*Elymus cinereus*), and cheatgrass (*Bromus tectorum*). Other grasses include western wheatgrass, Indian ricegrass, and Thurber needlegrass (*S. thurberiana*). Forbs vary widely in species and abundance but can include *Lupinus* sp., *Phlox* sp., *Aster* sp., *Senecio* sp., *Eriogonum* s *Rannuculus* sp., *Cryptantha* sp., *Mentzelia* sp., *Eriastrum* sp., *Castilleja* sp., *Machaeranthera* sp., *Argemone* sp., *Sphaeralcea* sp., *Nicotiana* sp., *Lygodesmia* sp., and *Chenopodium* sp.

Further north in pure stands of western juniper in eastern Oregon, bluebunch whe grass and Idaho fescue (*Festuca idahoensis*) are the dominant grasses (Franklin and Dyrness 1969). Sandberg bluegrass and Thurber needlegrass are common. Other grasses include bottlebrush squirreltail, needle-and-thread, cheatgrass, annual fescue (*Vulpia octoflora*), and prairie junegrass. Forbs are not very abundant, but the most common perennial forbs are *Agoseris* sp., *Achillea millifolium*, *Eriophyllum lanatum*, *Astragalus* sp., *Erigeron linearis*, and *Lupinus* sp.

Herbage yields of pinyon-juniper stands can vary considerably, depending on surface texture of soil and stage of succession (Thatcher and Hart 1974). Soils with a vesicular, massive, or platy surface layer may have very little grass regardless of the stage of plant succession (Thatcher and Hart 1974). However, a reasonable averag herbage yield for plant communities with moderate amounts of pinyon-juniper seems to

600 lb/acre (674 kg/ha) (Jameson and Reid 1965; Jensen 1972; Pieper and others 1971; Clary 1971). Yields on good soils with good precipitation can be as high as 1,400 lb/acre (1,573 kg/ha) (Pieper and others 1971; Springfield 1976).

Shrubs that dominate the understory of pinyon-juniper include big sagebrush (*Artemisia tridentata*), black sagebrush (*A. nova*), antelope bitterbrush (*Purshia tridentata*), shrub liveoak (*Quercus turbinella*), cliffrose (*Cowania mexicana*), Gambel oak (*Quercus gambelii*), serviceberry (*Amelanchier* sp.), and true mountain-mahogany (*Cercocarpus montanus*). Other shrubs that are associated in various amounts with pinyon-juniper include fringed sagebrush (*Artemisia frigida*), Wright silktassel (*Garrya wrightii*), currant (*Ribes cereum*), desert peach (*Prunus andersonii*), mountain lover (*Pachistima myrsinites*), skunkbush sumac (*Rhus trilobata*), ephedra (*Ephedra* sp.), curl-leaf mountain-mahogany (*C. ledifolius*), chokecherry (*Prunus virginiana*), mockorange (*Philadelphus lewisi*), pointleaf manzanita (*Arctostaphylos pungens*), winterfat (*Ceratoides lanata*), snowberry (*Symphoricarpos vaccinoides*), algerita (*Berberis fremonti*), Wright eriogonum (*Erigonum wrightii*), rabbitbrush (*Chrysothamnus nauseosus*), Apache plume (*Fallugia paradoxa*), blackbrush (*Coleogyne ramosissima*), fourwing saltbush (*Atriplex canescens*), broom snakeweed, dalea (*Dalea* sp.), horsebrush (*Tetradymia canescens*), and yucca (*Yucca* sp.). This wide variety of shrubs reflects the many different plant communities with which pinyon-juniper associates and has been taken from various references (Arnold and others 1964; Dwyer and Pieper 1967; Blackburn and others 1969; O'Rourke and Ogden 1969; Blackburn and Tueller 1970; Erdman 1970; Aro 1971; Clary 1971; Barney and Frischknecht 1974; West and others 1975; Klebenow and Bruner 1976; Springfield 1976; Young and Evans 1976a).

## Fire History

The historic role of fire in controlling the distribution of pinyon-juniper, particularly juniper, cannot be separated from the effects of drought and competition (Leopold 1924; Johnsen 1962; Burkhardt and Tisdale 1976). All three forces seem to have played a complementary role in limiting the distribution of juniper before grazing by domestic livestock was a factor. However, droughts and competition from grass probably only served to slow the invasion and growth of junipers in adajacent grasslands, because the trees are easily established during wet years (Johnsen 1962; Smith and others 1975), especially where shade is present (Meagher 1943). Then fire, occurring about every 10 to 30 years (Leopold 1924), kept the junipers restricted to shallow, rocky soils and rough topography (Arend 1950; Burkhardt and Tisdale 1969; O'Rourke and Ogden 1969). For the last 70 years, however, heavy livestock grazing has reduced grass competition as well as fuel for fires. Reduced competition from grasses has permitted pinyon and juniper to invade adjacent communities rapidly (Nabi 1978) and the reduced number of fires, each of a lower intensity than the fires before heavy grazing, has left the juniper invasion unchecked (fig. 10).

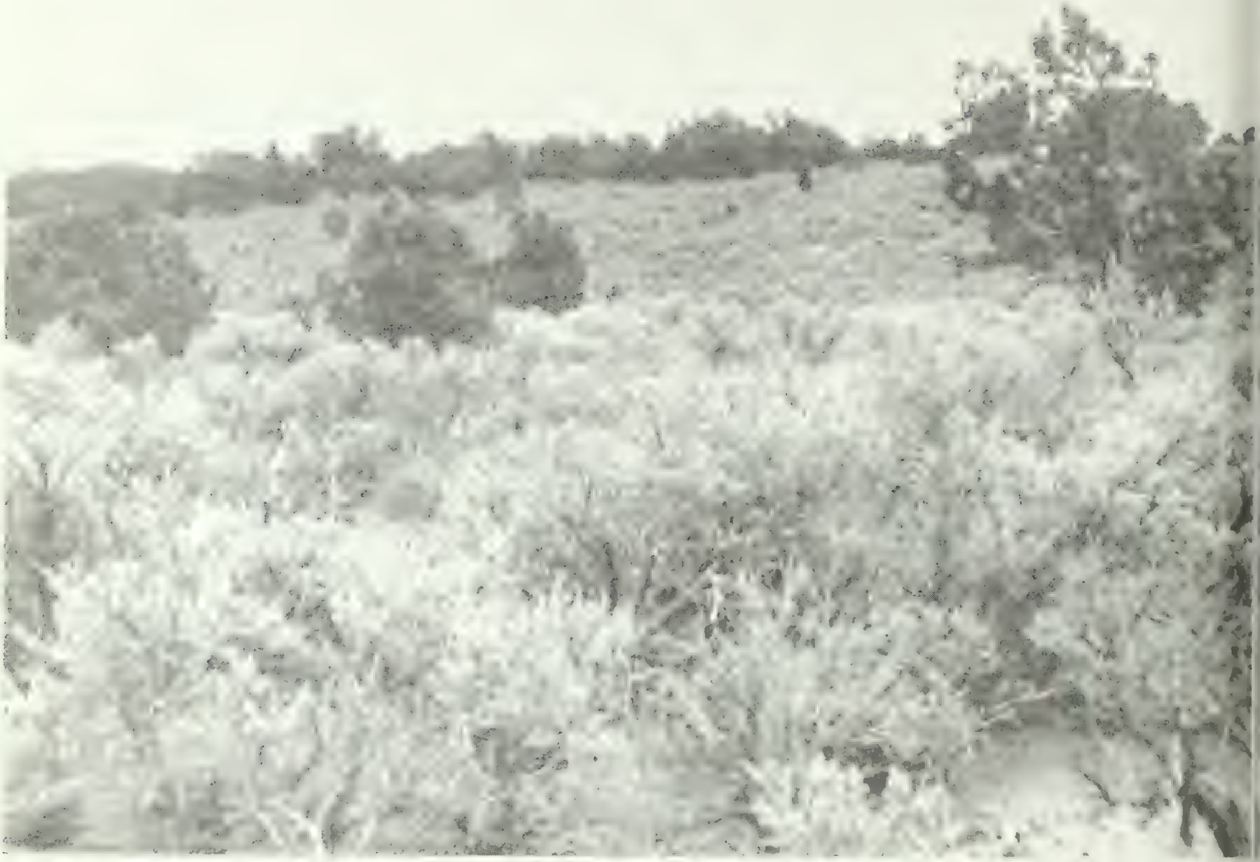

*Figure 10.--Pinyon and juniper invading a sagebrush community in Nevada. (University of Nevada photo.)*

## Ecological Effects of Fire

*Pinyon and juniper*

The effect of fire on pinyon and nonsprouting juniper trees depends largely upon the height of trees, herbaceous fuel, weather conditions, and season. In open pinyon-juniper stands with an understory of 600 to 1,000 lb/acre (674 to 1,124 kg/ha) of fine fuel, Jameson (1962) and Dwyer and Pieper (1967) found that pinyon and juniper were easily killed by spring fires if trees were less than 4 ft (1.2 m) tall when air temperature was 70° to 74°F (21° to 23°C), relative humidity 20 to 40 percent and wind speed 10 to 20 mi/h (16 to 32 km/h). Lower air temperatures in January [49° to 54°F (9° to 12°C)], a relative humidity of 44 percent, and a wind speed of 6 to 8 mi/h (10 to 13 km/h) caused a very spotty burn in which crown kill for trees 2 to 4 ft (0.6 to 1.2 m) tall varied from 30 to 70 percent. Mortality 2 years after the burn, however, was 70 percent (Jameson 1962). A wildfire in June when air temperature was 97°F (36°C), wind was 10 to 15 mi/h (16 to 24 km/h), and relative humidity was 17 to 25 percent resulted in 100 percent kill of all trees less than 4 ft (1.2 m) tall, but was no more effective on taller trees than when air temperatures were 70° to 74°F (21° to 23°C) (Jameson 1962).

Trees taller than 4 ft (1.2 m) in open pinyon-juniper stands are difficult to kill nless heavy accumulations of fine fuel lie beneath the trees. On the wildfire studied y Dwyer and Pieper (1967), only 24 percent of the pinyon and 13.5 percent of the juniper that exceeded 4 ft (1.2 m) died. Jameson (1962) found that most juniper taller han 4 ft (1.2 m) had only a 30 to 40 percent crown kill, unless tumbleweeds had accumlated at the base of the trees. As a result of this added fuel, 60 to 90 percent of he crowns were killed, particularly for those of trees 8 to 10 ft (2.4 to 3.0 m) tall. ast of the pinyon-juniper zone in Texas, juniper trees up to 12 ft (3.7 m) tall were illed easily when fine fuel was 2,000 lb/acre (2,247 kg/ha) or higher (Wink and Wright 973).

Trees in closed stands of pinyon-juniper (fig. 11) with no grass or sagebrush in he understory are difficult to kill because fires do not carry easily (Arnold and thers 1964; Blackburn and Bruner 1975). In 14- to 18-inch (35- to 45-cm) rainfall reas, dense stands [495 to 988 trees/acre (1,223 to 2,440/ha)] of mixtured pinyon-uniper can be burned on hot days, but pure stands of juniper are almost impossible to urn (Blackburn and Bruner 1975). In the Great Basin it is commonly believed that inds more than 35 mi/h (56 km/h) would be required to burn pure stands of juniper. hus, many attempts to burn such stands have failed (Arnold and others 1964; Aro 1971). s the proportion of pinyon to juniper increases and the density increases, the stands re easier to burn (Truesdell 1969; Blackburn and Bruner 1975).

*igure 11.--Dense, closed stand of pinyon and juniper with no understory, in Nevada. (University of Nevada photo.)*

Mixtures of sagebrush and pinyon-juniper are common throughout the Great Basin, and it is feasible to burn and kill large pinyon and juniper trees in these communitie (Bruner and Klebenow 1979). Most of the work done by Bruner and Klebenow has been done in pinyon-juniper stands with 45 to 60 percent shrub and tree cover wher air temperature was 60° to 75°F (16° to 24°C), relative humidity was below 25 percent, and maximum wind speed was 5 to 25 mi/h (8 to 40 km/h).

Alligator juniper and redberry juniper are the only sprouting species. Smith an others (1975) found that if the tops of redberry juniper trees were removed before th reached 12 years of age, 99 percent mortality could be expected. Older trees were not studied. This data implies that if subjected to fire every 10 years or so, sprouting species of juniper may have a difficult time invading grasslands. Schroeder (1956 un found that about 40 percent of alligator juniper trees less than 15 ft (4.6 m) tall could be killed by burning individual plants.

*Grasses and Forbs*

In Utah the most abundant annual forbs during the first stage of succession are pale alyssum (*Alyssum alyssoides*), flixweed tansymustard (*Descurainia sophia*), sunflower (*Helianthus annuus*), coyote tobacco (*Nicotiana attenuata*), and Russian thistle (*Salsola pestifer*) (Barney and Frischknecht 1974). Generally, however, none of these forbs constitute a large amount of cover on pinyon-juniper burns (Arnold and others 1964; Barney and Frischknecht 1974). Cheatgrass brome (*Bromus tectorum*) is usually the most abundant annual and has a cover value as high as 12.6 percent on 3-year-old burns. Thereafter, it gradually declines to 0.9 percent over a period of 20 years (Barney and Frischknecht 1974). On some sites, however, cheatgrass may never show up (Klebenow and others 1976) which might be used as a guide as to whether some areas ca be reclaimed to grasses. In Nevada, tapertip hawksbeard (*Crepis acuminata*) and *Lupin* sp. increase abundantly after fire (Klebenow and others 1976). *Balsamorhiza* sp. and *Castilleja* sp. also come back reasonably well (Klebenow and others 1976).

The composition of perennial grasses varies with location, as discussed earlier. In the northern latitudes west of the Rocky Mountains, cool-season grasses dominate, with a gradual transition to dominance of blue grama eastward in shortgrass plains an southward in central Arizona and New Mexico. Vallentine (1971) has cited a number of authors as to the tolerance of various grasses to fire. Species that are only slightl damaged by fall fires include bluebunch wheatgrass, Indian ricegrass, galleta grass (*Hilaria jamesii*), bottlebrush squirreltail, Great Basin wildrye, and blue grama. Th moderately affected by fire include prairie junegrass, needle-and-thread, Thurber needlegrass, and threeawns. Species severely affected by fire include ring muhly, sideoats grama, and Idaho fescue. Sandberg bluegrass, cheatgrass, western wheatgrass, and crested wheatgrass are unaffected by fall fires.

*Shrubs*

Vigorous sprouters after fire include serviceberry, Wright silktassel, shrub live oak, skunkbush sumac, true mountain-mahogany, desert bitterbrush, chokecherry, mockorange, winterfat, snowberry, algerita, rabbitbrush, fourwing saltbush, and horsebrush. Weak sprouters include antelope bitterbrush, curlleaf mountain-mahogany, snakeweed, mountai lover, yucca, fringed sagebrush, and Wright eriogonum. Antelope bitterbrush and mountain lover are extremely slow in recovering after fire (Nord 1965; McKell 1950). Cliffrose is eliminated on burns in Nevada (Klebenow and others 1976). Nonsprouting species include big sagebrush, black sagebrush. and blackbrush. Nevertheless, these nonsprouting species, except for blackbrush, have the ability to reestablish themselv quickly from seed. Blackbrush reestablishes very slowly (Bowns and West 1976; Jensen and others 1960, unpublished report).

### *Succession after Fire*

The general successional pattern after fire in pinyon-juniper of the Southern Rocky Mountains has been worked out by Arnold and others (1964) and most recently by Erdman (1970) and Barney and Frischknecht (1974). The order of vegetational changes in juniper woodland after fire as reported by Barney and Frischknecht is as follows: juniper woodland → fire → skeleton forest (dead trees) and bare soil → annual stage → perennial grass-forb stage → perennial grass-forb-shrub stage → perennial grass-forb-shrub-young juniper stage → shrub-juniper stage → juniper woodland.

Mature stands of juniper (100+ years) consist primarily of 35 percent bare-ground, 19 to 60 percent litter, a tree overstory that inhibits grass production (Johnsen 1962), and a few scattered shrubs and perennial and annual grasses (Arnold and others 1964; Clary 1971; Barney and Frischknecht 1974). Erosion is frequently a problem from the bare soils between trees in mature stands (Plummer 1958). After a fire, juniper seedlings and annuals begin to invade and reach maximum abundance in the first 3 to 4 years (Arnold and others 1964; Barney and Frischknecht 1974). Where partial shade is present, pinyon seedlings can also be abundant (Erdman 1970). The perennial-grass-forb stage usually follows in the fourth to sixth year. Little rabbitbrush (*Chrysothamnus viscidiflorus*) resprouts in the first year or two, and shrubs such as sagebrush (*Artemisia* sp.) and broom snakeweed (*Xanthocephalum sarothrae*) if they are present in the area begin appearing after the sixth year in plant communities in and around the Great Basin. In southwestern Colorado, Gambel oak, serviceberry, true mountain-mahogany, and antelope bitterbrush are the dominant shrubs (Erdman 1970). After 40 years, the shrubs begin to die out and the cover and density of juniper increases dramatically (Barney and Frischknecht 1974). Barney and Frischknecht (1974) found that Utah juniper begins to bear fruit at 33 years of age, which accounts for the ability of many juniper stands at 40 years of age or older to establish new trees and increase the number of trees per acre dramatically (Erdman 1970).

According to Erdman (1970), plant succession continues in three more stages. The open shrub stage becomes a thicket in about 100 years. As the sere progresses toward climax, the trees begin to overtop the shrubs and gradually suppress the shrubs as the forest matures. After several centuries, the understory is composed mainly of a sparse shrub component, some grass, and several forbs. In the absence of disturbances, a climax pinyon-juniper forest occurs in about 300 years.

## Management Implications

In open stands of pinyon-juniper in the Southwest, fire can be used effectively to kill pinyon and juniper trees less than 4 ft (1.2 m) tall. Taller trees are very difficult to kill, even with hot fires, unless tumbleweeds have accumulated at the tree bases. Thus, open stands of pinyon and juniper trees can be eliminated only by chaining or dozing followed by burning to render the microclimate unfavorable for tree seedlings.

Several management agencies have tried various techniques (Arnold and others 1964; Aro 1971; Clary 1971; Blackburn and Bruner 1975) to reclaim closed pinyon-juniper stands (no understory of grasses or shrubs). Prescribed burning, or some combination of burning with other treatments (followed by artificial seeding when necessary), is the most effective procedure (Aro 1971; Springfield 1976). Without any prior treatment, burning must be done on hot days 95° to 100°F (35° to 38°C) with low relative humidity and 8 to 20 mi/h (13 to 32 km/h) winds, conditions considered too hazardous by most land managers (Arnold and others 1964). Thus, mechanical treatment followed by burning is probably the most acceptable technique to reclaim dense stands of pinyon-juniper, even though it is expensive. Burning should be delayed 2 to 3 years after chaining to assure that most of the pinyon and juniper seeds have germinated (Meagher 1943).

Grasses will increase dramatically following burning and seeding treatments in closed stands of pinyon-juniper. Herbage yields on the Hualpai Indian Reservation in northern Arizona, seeded with crested wheatgrass, western wheatgrass, weeping lovegras and yellow sweetclover (*Melilotus officinalis*), produced 1,660 lb/acre (1,865 kg/ha) compared to 60 lb/acre (67 kg/ha) for the unburned control (Aro 1971). On another large-scale burning and seeding program in pinyon-juniper woodland, Aro (1971) reporte that forage production increased 500 lb/acre (562 kg/ha). Pinyon-juniper communities in northern Arizona that were chained and seeded but not burned produced 981 lb/acre (1,102 kg/ha) of grasses, forbs, and shrubs 5 to 11 years after treatment, compared to 223 lb/acre (250 kg/ha) on control plots (Clary 1971). Where native grasses were present in the understory, reseeding was not necessary (Aro 1971).

Mixtures of sagebrush and pinyon-juniper can be burned without prior treatment. Generally, thick stands with 45 to 60 percent cover are selected for burning and burned into areas with less shrub cover. Some areas are left to reseed naturally, but aerial seeding is usually considered desirable.

Pinyon-juniper stands converted to grassland should be reburned about every 20 to 40 years. A definite time is difficult to set because reinvasion of pinyon and junipe is dependent on climate, kind of initial treatment, time span between treatments, intensity of the burn, and grazing intensity after the burn. A general guide would be to reburn when the tallest pinyon or juniper tree reaches a height of 4 ft (1.2 m).

## State-of-the-Art

More research is needed on techniques for burning closed stands of juniper and mixed stands of sagebrush and pinyon-juniper. Although we have a general knowledge of and procedures for prescribed burning, we are not satisfied with either. Closed stands have been burned successfully and economically in northern Arizona without prior treatment, but we need to know where this kind of burning can and cannot be done. Can the technique be applied to areas with less than 200 trees per acre (494 trees per hectare) or areas with less than 600 lb/acre (674 kg/ha) of herbaceous understory? Some reliable guides are needed.

We have reasonably good baseline data for burning mixed stands of pinyon-juniper and sagebrush with no herbaceous understory. However, we need to know more about setting the boundaries (based on cover and weather) for areas to be burned. Should firelines be chained and burned before burning a large block of mixed sagebrush and pinyon-juniper? How wide should the firelines be?

We know reasonably well how to burn open pinyon-juniper grasslands. We need to know the minimum amount of fine fuel (herbaceous understory) that will carry a fire. Our estimate is 600 to 700 lb/acre (674 to 786 kg/ha), which is about the productive potential of a large percentage of the pinyon-juniper acreage.

Our largest void of information on pinyon-juniper communities is the response of the understory species to fire. We have pieces of information, but a number of the shrubs and some cool-season grasses deserve more study. Alligator juniper needs to be studied in more detail. We need to know how different age classes of this species respond to fire. Our present data indicate that young trees may be more susceptible to fire than the old trees.

Guidelines for reseeding burned pinyon-juniper stands would be helpful. Should drilling be done in preference to aerial seeding when possible? In untreated pinyon-juniper at what point is it advisable to supplement the natural perennial understory with artificial seeding?

# PRESCRIBED BURNING GUIDES

## Sagebrush-Grass Communities

### *Big Sagebrush and Grass*

Sagebrush is difficult to burn unless there is at least 600 to 700 lb/acre (674 to 786 kg/ha) of herbaceous fuel (Beardall and Sylvester 1976). Moreover, burning should not be considered a management tool unless the cover of big sagebrush exceeds 20 percent (Pechanec and others 1954). After deciding to burn, try to avoid burning immediately after heavy seed crops, because sagebrush can rapidly reoccupy the burned area during years with good moisture (Pechanec and others 1954; Johnson and Payne 1968). Early spring or late summer (August) burns may be the most preferable (Blackburn and Bruner 1975; Beardall and Sylvester 1976). Soils should be moist down to 12 or 18 inches (30 to 45 cm) before burning in the spring, but in the fall soil moisture is not as critical for most plant species.

Various procedures have been used to conduct prescribed burns in sagebrush-grass communities. In southeastern Idaho Pechanec and others (1954) plowed a single 8-ft (2.4-m) fireline completely around an area. On the downwind edge of the fireline, they plowed another line with the berm pushed to the center of the plowed area to stop firebrands rolling along the ground. Then Pechanec and others (1954) plowed a final line 100 to 200 ft (30 to 61 m) inside the area to be burned, parallel to the double fireline. This uncleared strip [usually the north and east sides of a 400- to 600-acre (162- to 243-ha) block] was burned in late August with backfires or strip headfires in the forenoon, with the wind 5 to 8 mi/h (8 to 13 km/h) and relative humidity about 40 percent. After the uncleared strip had been burned, the remaining area was burned with a headfire, starting about 2:30 to 3:00 p.m., presumably when air temperature was above 75°F (24°C), relative humidity was 15 to 20 percent, and wind was 8 to 15 mi/h (13 to 24 km/h) (Ralphs and others 1976).

A burning technique similar to that of Pechanec and others (1954) was used at the Benmore Experimental Range in central Utah (Blackburn and Bruner 1975). Firelines varied from 20 to 150 ft (6.1 to 45.7 m), with the narrow lines being on the upwind side (Davis 1976). Davis (1976) states that based on theoretical values and experience, flash fuels can be expected to ignite 50 to 90 ft (15.2 to 27.4 m) ahead of an advancing front in sagebrush-grass. However, he has seen spot fires start 200 ft (61 m) in advance of the flame front (Davis 1978, personal communication). This implies that firelines on the downwind side of a sagebrush-grass fire should be at least 200 ft (61 m) wide.

Martin and others (1977) have used a wet line in lieu of a plowed line in cheatgrass (*Bromus tectorum*). This technique involves wetting a line and letting the fire back away from it. This can be done easily in cheatgrass on smooth terrain; however, n rough topography, this technique would not be feasible. More attention needs to be given to the preparation of safe firelines without the use of dozers (Davis 1976). Fire retardants and the use of chemicals are alternatives, but have not been adequately tested to be recommended.

*Recommendation*: Based on the above data and research by Ralphs and others (1976) we recommend dozing a 10- to 12-ft (3- to 3.7-m) fireline around the area to be burned [preferably about 450 acres (182 m) according to Davis (1976)]. Then strip headfire a 200 ft (61 m) strip on the leeward sides during the morning hours when wind is 5 to 8 mi/h (8 to 13 km/h) and relative humidity is about 40 percent. As the fire backs up in heavy fuel beyond the 200 ft (61 m) strip, use a pumper to put the fire out. About 3:00 p.m. headfire the remaining area when air temperature is above 75°F (24°C), relative humidity is 15 to 20 percent, and wind is 8 to 15 mi/h (13 to 24 km/h) (Ralphs and others 1976).

### *Big Sagebrush and Low Sagebrush*

Where dense stands of big sagebrush are mixed with low sagebrush (*Artemisia arbuscula*) (fig. 12), no firelines need to be prepared because fires will not carry i low sagebrush even during a hot day with winds up to 25 mi/h (40 km/h) (Beardall and Sylvester 1976). Thus, such stands can be burned on warm days with steady winds whenever it is convenient.

*Recommendation*: Beardall and Sylvester (1976) suggest burning in early spring when relative humidity is below 60 percent, wind speed is above 8 mi/h (13 km/h), and when there is more than 600 to 700 lb/acre (674 to 786 kg/ha) of fine fuel. Late summer burning has not been tested in areas dominated by low sagebrush because of the potential to harm sensitive grasses such as Idaho fescue (*Festuca idahoensis*).

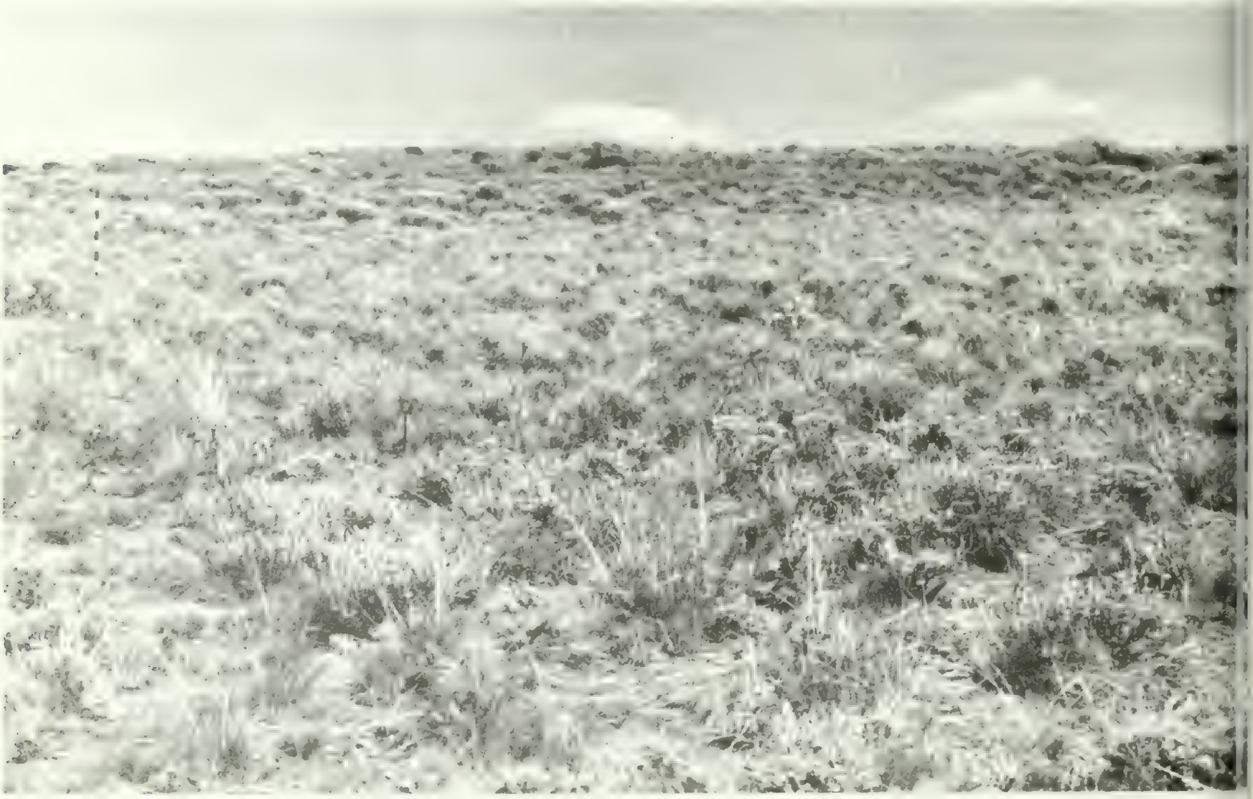

*Figure 12.--Low sagebrush community with Idaho fescue. Fine fuel is usually inadequa to carry a fire. (University of Idaho photo.)*

## Pinyon-Juniper Communities

### *Open Stands of Pinyon-Juniper with Grass Understory*

In this vegetation type, fire kills only pinyon and juniper trees less than 4 ft (1.2 m) tall (Jameson 1962; Arnold and others 1964; Dwyer and Pieper 1967). Moreover we believe that at least 600 to 700 lb/acre (674 to 786 kg/ha) of fine fuel is needed to carry a fire. Trees taller than 4 ft (1.2 m) will not be killed unless tumbleweed have accumulated at the base (Jameson 1962).

*Recommendation*: Doze a fireline 10 to 12 ft (3.0 to 3.7 m) wide around the area o be burned. About 450 acres (182 ha) would be a good-sized unit (Davis 1976). Strip eadfire a 100-ft (30-m) strip on the leeward sides of the planned burn during evening r morning hours in the spring. Where fire continues to back up beyond the 100-ft 30-m) strip, put it out with a pumper. Then headfire the remainder of the area when he air temperature is 70° to 74°F (21° to 23°C), relative humidity is 20 to 40 percent, nd windspeed is 10 to 20 mi/h (16 to 32 km/h) (Jameson 1962; Dwyer and Pieper 1967).

### *losed Stands (No Grass or Shrub Understory) of Pinyon and Juniper*

Mixtures of pinyon and juniper with 300 or more trees per acre (741 or more trees er hectare) in 14- to 18-inch (35- to 45-cm) rainfall areas can be burned on hot, indy days if prepared properly (Truesdell 1969; Blackburn and Bruner 1975). However, losed stands of juniper are almost impossible to burn (Blackburn and Bruner 1975) nd would probably require winds in excess of 35 mi/h (56 km/h) to carry a fire. As he proportion of pinyon to juniper increases and density increases, the stands are asier to burn (Hester 1952; Truesdell 1969; Blackburn and Bruner 1975).

*Recommendation*: Where firebrands are not a problem on a hot day (i.e., burning nto the Grand Canyon or on top of a mesa), prepare dense stands of pinyon and juniper or burning in March or April. Clear a strip 20 to 50 ft (6.1 to 15.2 m) wide every .25 mile (0.4 km) and push windrows against the green trees on the windward side. et the material cure for 60 to 90 days. Then in late June or early July, burn when emperatures vary from 80° to 95°F (27° to 35°C), relative humidity is 4 to 8 percent, nd winds exceed 8 mi/h (13 km/h) (Truesdell 1969; Blackburn and Bruner 1975).

Where firebrands are of concern, or where the pinyon-juniper stands are predomiantly juniper, a more acceptable method of killing trees in closed stands may be to hain, burn, and seed (Aro 1971; Stinson 1978). Two or three months after chaining, inyon and juniper can be burned with little risk when the wind is blowing into an ntreated closed stand (fig. 13) or into a recently treated area with little fine fuel. urn the lee sides of the area (61 m) during the morning hours when the fire danger is ow (Stinson 1978). Then, burn the remainder of the area under the following conditions: ir temperature 90° to 100°F (32° to 38°C), relative humidity less than 10 percent, wind to 10 mi/h (13 to 16 km/h) (Stinson 1978).

It takes large crews to do this kind of burning because much of the material is in iles or windrows. Burning chained areas removes the trash and young trees that provide n ideal microenvironment for the establishment of pinyon and juniper seedlings (Meagher 943) and also provides a good seedbed for grasses.

Another alternative for closed pinyon and juniper stands is to use chaining to onstruct firelines (Davis 1976). Optimum width is not known. A 300-ft (91-m) line hould be adequate because there is very little fine fuel that can be ignited by glowing mbers. The lines could be chained in the winter and then burned under moderate onditions in the spring or summer when surrounding vegetation is green (Davis 1976). eather with temperatures of 60° to 75°F (16° to 24°C), windspeed less than 8 mi/h 13 km/h), and relative humidity about 25 percent should be adequate for burning such irelines, although this has not been documented. It would seem preferable to burn nder cool conditions so that most of the manpower could be used to light the dead aterial, rather than to patrol for spotfires.

After the firelines have been burned out, then the windrows (also prepared in inter) on the upwind side could be lit on a dry, hot, windy day in June or July. Air emperatures should be 80° to 95°F (27° to 35°C), relative humidity 4 to 8 percent, and indspeed in excess of 8 mi/h (13 km/h).

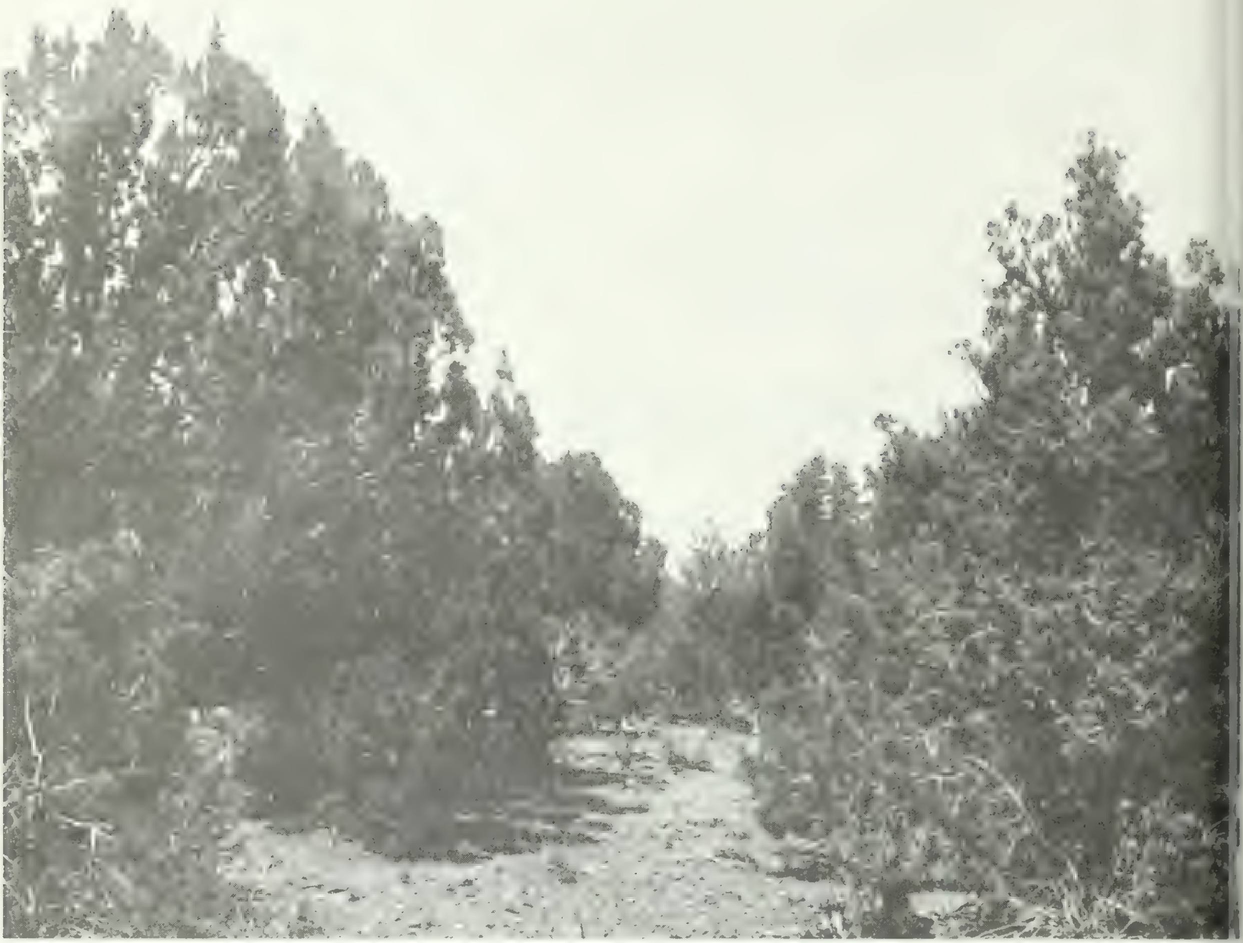

*Figure 13.--Burning into closed stands of juniper such as this one should be reasona safe because little fine fuel is on the ground.*

### *Mixture of Pinyon-Juniper and Sagebrush*

Mixtures of sagebrush and pinyon-juniper are common throughout the Great Basin. Dense patches of pinyon-juniper and sagebrush that vary in size from 5 to 60 acres (2 to 24 ha) can easily be burned without preparing firelines (Bruner and Klebenow 1979).

*Recommendation*: Klebenow and Bruner (1976) have found that mixtures of pinyon-juniper and sagebrush with a total shrub and tree cover of 45 to 60 percent can be burned when spring air temperatures vary from 60° to 75°F (16° to 24°C), relative humidity is below 25 percent, and maximum windspeeds vary from 5 to 25 mi/h (8 to 40 km/h). They recommend using the "White Pine County Formula" to determine whether or not to burn (Bruner and Klebenow 1979) where,

Index = Maximum wind (mi/h) + Shrub and tree cover (%) + Air temperature (°F).

If the index is 110 or higher, a fire will carry and will kill large pinyon and juni trees. If the index is above 130, it is too dangerous to burn. Retorching of trees is necessary until the index is over 125.

# FIRE EFFECTS DATA FOR PLANT SPECIES

## Response of Grasses to Burning

*Bluegrasses*

In general, bluegrasses (*Poa* sp.) are slightly damaged by burning. Wright and Klemmedson (1965) observed no change in basal area of Sandberg bluegrass (*Poa sandbergii*) during any season regardless of the size of plants. These plants were mature, dry, and varied in diameter from 1 to 3 inches (2.5 to 7.5 cm). Tisdale (1959) reported some damage to Sandberg bluegrass in communities with 7 to 14 percent sagebrush cover. This damage was possibly caused by plants being old and pedestaled. High mortality has been observed in southern Oregon when plants are pedestaled (Hammersmark 1977, personal communication). An August wildfire in northeastern California caused decreases in plant numbers (Countryman and Cornelius 1957). Moomaw (1957) found no damage in eastern Washington. Uresk and others (1976) measured a 57 percent decrease in basal area of cusick bluegrass (*P. cusickii*) after an August wildfire.

On the upper Snake River Plains of Idaho, Nevada bluegrass (*P. nevadensis*) and Sandberg bluegrass showed little change in production for 3 years after burning (Harniss and Murray 1973). This initial static period was followed by increased yields, with the burned area producing about 1.5 times more than the unburned. Thirty years after burning, yield was substantially lower on both burned and unburned areas, although the burned area was producing twice as much as the unburned. Big bluegrass (*P. ampla*) is not mentioned in the literature but, due to larger clone size and greater potential accumulation of litter in the crown, it would be expected to incur slightly more damage than other bluegrasses.

*Cheatgrass*

Cheatgrass (*Bromus tectorum*) is not appreciably affected by burning although production may be reduced for the first year. Abandoned fields on the Snake River Plains dominated by cheatgrass were changed to primarily tumblemustard (*Sisymbrium altissimum*) and Russian thistle (*Salsola kali*) after burning for 2 to 3 years. Cheatgrass dominated these fields during the next 2 to 3 years (Piemeisel 1938). Burning was found to reduce stands of cheatgrass in eastern Washington, presumably because of seed destruction (Robocker and others 1965). Depending on the intensity of burn, germinable cheatgrass seed can be reduced 80 to 99 percent (Young and others 1976). This reduction left from 3 to 33 germinable seeds/ft$^2$ (32 to 374/m$^2$), but as few as 5 cheatgrass seeds/ft$^2$ (54/m$^2$) moderately reduced establishment of crested wheatgrass. June and July burns reduced cheatgrass plant numbers to 14 and 11/ft$^2$ (150 and 118/m$^2$) compared to 41, 45, and 124 plants/ft$^2$ (439, 481, and 1,327 plants/m$^2$) on August, October, and November burns, respectively, near Boise, Idaho (Pechanec and Hull 1945). These reductions are only temporary, for annuals produce abundant seed the year after a burn. Early summer burns will kill perennial grasses and allow cheatgrass to increase sharply.

Cheatgrass can rapidly occupy a burned area if only a few seeds are available (Countryman and Cornelius 1957). Barney and Frischknecht (1974) reported that cheatgrass cover declined during the first 22 years after fire, then stablized. This cover change varied from 12.6 percent on 3-year-old burns to 0.9 percent on the oldest burns.

### *Idaho Fescue*

The majority of evidence indicates that Idaho fescue (*Festuca idahoensis*) is severely damaged regardless of when or where it is burned (Pechanec and Stewart 1944; Blaisdell 1953; Harniss and Murray 1973). After a period of 30 years, Idaho fescue was just approaching its former abundance on the upper Snake River Plains (Harniss and Murray 1973). However, the annual precipitation is 14 in (35 cm) in this area, which is marginal for Idaho fescue in this region of Idaho. As a result of a summer wildfi in eastern Washington, Idaho fescue mortality was 27 percent, with a reduction in basal area of 50 percent (Conrad and Poulton 1966). In northeastern California, basa area of Idaho fescue was reduced approximately 80 percent by an August wildfire (Coun-man and Cornelius 1957).

Mid-May burns in eastern Oregon resulted in 30 percent mortality and a 48 percen reduction in basal area (Britton and Sneva 1977, personal communication). However, wh the plants were dormant in the fall, no mortality resulted although there was a 34 percent reduction in basal area. Phillips (1977, personal communication) observed th in central Oregon, wildfires were more damaging to Idaho fescue on coarse soils than on fine-textured soils. Good soil moisture was found beneficial to Idaho fescue survi during spring burns in Nevada (Beardall and Sylvester 1976).

### *Indian Ricegrass*

Indian ricegrass (*Oryzopsis hymenoides*) is important in sagebrush-bunchgrass communities only in localized situations. As such, it has not been the subject of intensive investigations. Pechanec and Stewart (1944) mention it as being slightly damaged and slow to increase after burning.

In west-central Utah, Indian ricegrass was found to be an important species on burned areas (Barney and Frischknecht 1974). Therefore, it probably has good survival characteristics. Spring burning in Utah did little damage to Indian ricegrass; growt began about 3 weeks after burning (Jensen 1977, personal communication). Summer wildfires in Nevada reduce basal area, but little mortality was noted (Wagner 1977, perso communication).

### *Junegrass*

In eastern Oregon, junegrass (*Koeleria cristata*) has been found to be one of the most fire-resistant perennial bunchgrasses (Britton and Sneva 1977, personal communication). Burning in mid-May reduced basal area by 32 percent, with 20 percent mortality. Burning in mid-June just after seed-set reduced basal area 18 percent, with no mortality; burning in mid-October produced only slightly more damage. Light damage is probably due to the relative small size of the typical junegrass clone.

Fall burning in North Dakota increased the frequency of junegrass on a sandy soil (Dix 1960). Twelve years after burning in Idaho, junegrass yield was higher on burned areas than on unburned areas (Blaisdell 1953). Countryman and Cornelius (1957) reported a slight decrease in junegrass due to a wildfire although the sample was too small for adequate interpretation.

### *Needlegrasses*

Most needlegrasses (*Stipa* sp.) are damaged by burning, especially during the first year. Harniss and Murray (1973) reported a severe reduction the first year after burning needle-and-thread (*Stipa comata*). Season of burn rather than burning intensity or plant size was found to be the most critical factor in mortality of needle-and-thread (Wright and Klemmedson 1965). June burns killed all of the small plants and 90 percent of the large plants. In July, 20 percent of the burned plants died but no mortality was recorded for August treatments. Among large plants, the average basal area reduction after June burns was 99.6 percent; July burns, 96 percent; and August burns, 68 percent. The reduction in basal area for the small plants following June burns was 100 percent, July burns, 82 percent. Small plants burned in August exhibited some thinning of the crown. This damage was related to the intolerance of needle-and-thread grass to herbage removal and the large amounts of dead material per unit basal area (Wright 1971). In western North Dakota, fall burning decreased needle-and-thread grass frequency by 11 percent on sandy soils but increased frequency by 10 percent on a clayloam soil. Observations in southern Idaho indicate that with moderate grazing treatments, needle-and-thread grass requires 4 to 8 years after burning to fully recover.

Twelve years after burning, Blaisdell (1953) observed that needle-and-thread grass and Columbia needlegrass (*S. columbiana*) were not significantly affected by any intensity of burn, although the former produced 10 to 26 lb/acre (11 to 29 kg/ha) on burned than on unburned range. Western needlegrass (*S. occidentalis*) was reduced the first year after an August wildfire in northeastern California (Countryman and Cornelius 1957). By the third year after burning, western needlegrass had almost doubled in basal area as compared to the unburned area.

Thurber needlegrass (*S. thurberiana*) is probably the least fire resistant needlegrass. Uresk and others (1976) found that an August wildfire reduced the basal area by 53 percent, with a concurrent decrease in leaf length. In eastern Oregon, Thurber needlegrass was severely damaged by burning (Britton and Sneva 1977, personal communication). Plants burned in mid-May had 80 percent mortality and the basal area was reduced by 93 percent. In mid-June, mortality increased to 90 percent and basal area was reduced 93 percent. Least damage resulted from October burns, with no mortality and a 48 percent reduction in basal area. Wright and Klemmedson (1965) reported similar results for Thurber needlegrass.

### *Sedges*

Sedges show various responses to burning. Pechanec and Stewart (1944) list threadleaf sedge (*Carex filifolia*) as being severely damaged; Douglas sedge (*C. douglasii*) was classed as undamaged. This difference was attributed to the ability of Douglas sedge to initiate growth from basal buds. Twelve years after burning, Blaisdell (1953) reported sedges were producing more on light burns but less on moderate and heavy burns in one area while the opposite trend was found on another area. Threadleaf sedge was found to be producing on the average more on burned areas as compared to unburned areas, therefore initial damage by burning was not permanent. Douglas sedge was reduced in number of plants as a result of a wildfire in northeastern California (Countryman and Cornelius 1957).

### *Bottlebrush Squirreltail*

Bottlebrush squirreltail (*Sitanion hystrix*) is one of the more fire resistant bunchgrasses, although some damage is apparent. In southern Idaho, Wright and Klemmedson (1965) observed no plant mortality as a result of burning. There was some reduction in basal area for plants burned in June but it was most apparent (15 percent reduction) in July for both large and small plants. In August only the large plants responded to hot burns, with a 16 percent reduction in basal area. The greater overall damage in July was probably due to higher initial burn temperatures in the plant crown. Wright (1971) reported that burning generally reduced herbage production of bottlebrush squirreltail most during May and somewhat less thereafter. In northeastern California, bottlebrush squirreltail plants were found to increase in winter the first year after wildfire but decreased by the third year (Countryman and Cornelius 1957).

Burning bottlebrush squirelltail plants in a drought year in eastern Oregon resu ed in 30 percent mortality in mid-May (Britton and Sneva 1977, personal communication). o mortality was recorded for mid-June or October burns. The mid-May burns reduced basa area by 73 percent while the October burn reductions were 48 percent.

In west-central Utah, bottlebrush squirelltail cover was found to increase durin the first 5 to 6 years after burning (Barney and Frischknecht 1974). This increase was stable for up to 40 years. Often bottlebrush squirelltail plants are very small and will increase in size rapidly after a burn. The larger plants, however, would be slightly harmed (Wright 1971; Britton and Sneva 1977, personal communication).

*Wheatgrasses*

Fall burning of crested wheatgrass (*Agropyron desertorum*) results in only small changes in the stand. Density of plants should remain unchanged (Kay 1960), althoug yield may be reduced during the first growing season after burning (Lodge 1960). Aft growth initiation, spring burning can reduce yield for 2 years (Lodge 1960). Creste wheatgrass seedings are considered fire resistant because many observers report that wildfires move only a few feet (2 or 3 m) into a seeding.

Bluebunch wheatgrass (*A. spicatum*) is slightly affected by burning. Twelve year after burning, Blaidell (1953) found an almost twofold increase in yield compared to unburned controls. After 30 years, yield of bluebunch wheatgrass on the same area wa slightly below the controls (Harniss and Murray 1973). Cover of bluebunch wheatgras remained uniform in west-central Utah for 40 years after burning before the juniper overstory caused a decline (Barney and Frischknecht 1974).

The negative effects of burning bluebunch wheatgrass are usually evident only i the first year after burning. Uresk and others (1976) measured decreases in leaf lengths and basal area, but an increase in yield 1 year after burning in eastern Washington. These results are similar to the 29 percent reduction in basal area and 1 percent mortality observed in the same region by Conrad and Poulton (1966). In eastern Oregon during mid-May, burning decreased the basal area by 78 percent with a 50 percent mortality. When plants were burned during the fall, there was no mortalit but a reduction in basal area of 47 percent compared to preburn measurements of the same plants (Britton and Sneva 1977, personal communication). Effects of burning (Wright 1974) were magnified by an extremely dry year. Bluebunch wheatgrass will usually return to preburn production in 1 to 3 years (Blaisdell 1953; Moomaw 1957; Conrad an Poulton 1966; Uresk and others 1976; Daubenmire 1963, unpublished report).

Response of other wheatgrasses falls somewhere between crested wheatgrass and blu-bunch wheatgrass with the exception of the rhizomatous wheatgrasses. Thickspike whea grass (*A. dasystachyum*) exhibits virtually no change 1 year after burning and after years produces about twice as much as unburned controls (Blaisdell 1953). It appeare that the more intense the burn the greater the response. In northeastern California a mixed wheatgrass stand was burned in the fall of the third growing season (Kay 196 The following summer, a 25 percent increase in stocking was measured, primarily due t rhizomes of intermediate wheatgrass (*A. intermedium*) and pubescent wheatgrass (*A. trichophorum*). Tall wheatgrass (*A. elongatum*) remained unchanged. In North Dakota, western wheatgrass (*A. smithii*) was unchanged in frequency regardless of site or soi (Dix 1960).

## Response of Forbs to Burning

Forbs generally respond better to burning than grasses. Where plant communitie have large proportions of forbs in the herbaceous component, burning may provide the best manipulation technique. Fall burning does not harm most forbs because they are often dry and disintergrated by this time. Pechanec and Stewart (1944) classified forbs according to their susceptibility to fire.

Due to lack of research evidence on individual forb species, no attempt will be nade to review each species mentioned in the literature. Instead, each article nentioning forbs will be abstracted.

Probably the best research treatment of forbs is from the prescribed burns onducted in Clark and Fremont Counties on the upper Snake River Plains of Idaho. This ork is presented in a series of three articles by Pechanec and others (1954); Blaisdell (1953); and Harniss and Murray (1973). Pechanec and others (1954) observed that the apidity of increase by the lightly damaged or undamaged species depended largely on hether the plant spreads by rootstocks. Those that do not, even though undamaged, ncrease slowly after burning. These include some of the more palatable species such s arrowleaf balsamroot (*Balsamorphiza sagittata*) and tailcup lupine (*Lupinus caudatus*). espite a quick recovery from burning, any increase in number of plants must await eed production.

Plant species spreading by rootstocks or root shoots are least harmed and spread ost rapidly after burning. These species include western yarrow (*Achillea lanulosa*), urpledaisy fleabane (*Erigeron corymbosus*), longleaf phlox (*Phlox longifolia*), flaxeaf plainsmustard (*Sisymbrium linifolium*), lambstongue groundsel (*Senecio integerrimus*), range arnica (*Arnica fulgens*), and common comandra (*Comandra umbellata*). Such species s western yarrow, longleaf phlox, and purpledaisy fleabane doubled in production within to 4 years.

Approximately 12 years after the burns in Clark and Fremont Counties, Blaisdell 1953) reevaluated the vegetation response. In Fremont County, he found total forb roduction was considerably higher on all burn intensities as compared to unburned areas. orb production in pounds per acre was unburned, 127; light burn, 191; moderate burns, 37; and heavy burn, 170 (143, 215, 266, and 191 kg/ha). Of the species mainly responible for the higher yield of forbs on burned areas, western yarrow, aster (*Aster* sp.), leabane, and goldenrods (*Solidago* sp.) are rhizomatous perennials. Littleaf pussytoes *Antennaria microphylla*), a suffrutescent forb of low forage value, and sticky geranium *Geranium viscosissimum*), a perennial rated fair forage, also contributed to the igher yield, especially on light and moderate burns. On the other hand, yield of notweed (*Polygonum douglasii*), an undesirable annual, was greatest on the heavy burn. he lower yield of plumeweed (*Cordylanthus ramosus*) on burned areas compared to unburned reas approached statisical significance.

The 1934 inventories showed a marked increase in total production of forbs on urned areas in relation to that on the unburned. This trend continued through the hird year, especially on burns of light and moderate intensity. Although much of hese early increases had disappeared by 1948, differences were still significant for ight and moderate burns.

Rhizomatous species on all burn intensities showed relative increases the first ear after burning, but subsequent trends were variable. On the other hand, uffrutescent forbs [pussytoes and eriogonum (*Eriogonum caespitosum* and *E. heracleoides*)], ecreased markedly, roughly proportionate to burn intensity, and then increased. nnuals, primarily gayophytum (*Gayophytum diffusum*), knotweed, plumeweed, and goseoot (*Chenopodium* sp.), made enormous relative increases in 1934, roughly in proportion o burn intensity. Portions of these relative increases persisted through 1936, but ad disappeared by 1948 on all but the heavy burn. The persistence of annuals on the eavy burn was shown by actual yield of knotweed, 26 lb/acre (29 kg/ha) on the heavy urn as compared to 7 lb/acre (7.9 kg/ha) on the control. Other perennial forbs enerally showed an initial but temporary increase after burning.

After 12 years, only the heavy burn in Clark County supported a significantly igher yield of forbs compared to the unburned area. It appeared that fleabane and hlox (both rhizomatous species) on burns of all intensities and lupines on the heavy urn were producing more than on the unburned ground. Apparently the effect of burning n the other forbs was negligible after 12 years.

In contrast with Fremont County, inventories of Clark County plots the year after burning showed a decrease in total forb production on burned areas in relation to the unburned. By the third year, considerable increases in relative yield were evident, but most of these early effects disappeared during the next 9 years. As in Fremont County, rhizomatous forbs generally increased the first year, but suffrutescent species, eriogonum and pussytoes, decreased markedly on all burns. Rhizomatous species continued to increase through the third year, then decreased. After the initial relative decreases, suffrutescent species increased throughout the study period and regained much of their original losses. With the exception of plumeweed, annuals were present only in very small amounts. Other perennial forbs increased the first year on burns of all intensities but trends in following years were not well defined.

By 1966, Harniss and Murray (1973) found little difference in forb production on burned and unburned plots. Although individual species were not mentioned, perennia forbs accounted for the bulk of the production.

Abandoned fields on the Snake River Plains dominated by cheatgrass were burned during the early 1930's (Piemeisel 1938). The first year after burning the major portion of the vegetation was tumblemustard and Russian thistle, with some flixweed tansymustard (*Descurainia sophia*). It took 2 to 3 years for the fields to again be dominated by cheatgrass. Near Dubois, Idaho, Mueggler and Blaisdell (1958) reported an increase in forb production after burning. Those species most benefited included timber poisonvetch (*Astragalus convallarius*), purpledaisy fleabane, and lupine. Forbs that were injured include littleleaf pussytoes and matroot penstemon (*Penstemon radicosus*).

In western North Dakota, Dix (1960) found that wild lettuce (*Lactuca pulchella*) decreased about 20 percent. The most dramatic decrease (63 percent) was on loamy fine sand. Red globemallow (*Sphaeralcea coccinea*) increased when present in the vegetation

Robocker and others (1965) found that burning decreased most forbs on a sandy soil in eastern Washington. Burning appeared to have reduced stands of tumblemustard, tansymustard (*Descurainia pinnata*), and whitlow-wart (*Draba verna*).

In west-central Utah, Barney and Frischknecht (1974) sampled burns ranging in age from 3 to more than 100 years. The most abundant forbs during the first stages of succession were pale alyssum (*Alyssum alyssoides*), flixweed tansymustard, sunflower (*Helianthus annuus*) coyote tobacco (*Nicotiana attenuata*), and Russian thistle. Because these forbs were abundant on recent burns, it can be assumed that they were not seriously damaged by burning.

Yarrow was found to decrease the first 2 years after burning in northeastern California (Countryman and Cornelius 1957). However, by the fifth year there was a 7.5-fold increase in crown area.

In eastern Oregon, tailcup lupine changed slightly in cover from an average of percent to more than 16 percent 1 year after fall burning (Britton and Sneva 1977, personal communication). The burns were in a dry year followed by a drier year. Hammersmark (1977, personal communication) observed in southern Oregon that astragalus, arrowleaf balsamroot, tapertip hawksbeard (*Crepis acuminata*), tailcup lupine, globemallow, and foothill deathcamas (*Zigadenus paniculatus*) were not damaged by wildfire. In Nevada, Wagner (1977, personal communication) measured a three-fold increase in frequency of longleaf phlox with no reduction in wild onion, astragalus, tapertip hawksbeard, lupines, globemallow, and foothill deathcamas as a result of wildfire.

## Response of Shrubs to Burning

*itterbrush*

The specific effect of fire on bitterbrush depends on the species and location
Nord 1965). For example, abundant resprouting of antelope bitterbrush (*Purshia*
*ridentata*) occurs in eastern Idaho (Blaisdell 1953; Blaisdell and Mueggler 1956),
imited resprouting occurs in central and northern Utah (Blaisdell and Mueggler 1956),
nd very little resprouting occurs in Oregon and California (Nord 1965). Billings
1952) reports that fire eradicates bitterbrush in the western Great Basin because it
arely root-sprouts in that region, and seeds of bitterbrush do not disseminate from
heir source. Klebenow and others (1976) reported that in Nevada resprouts of bitter-
rush generally died the year following burning. However, good production from seed
esulted from the burn. The natural frequency of fire in areas that contain antelope
itterbrush is probably not more than 41 to 50 years, if that often.

Generally speaking, antelope bitterbrush is a weak sprouter and living plants are
everely damaged by fire (Blaisdell 1953; Pechanec and others 1954; Countryman and
ornelius 1957; Nord 1965). For antelope bitterbrush to resprout regularly in areas
uch as southeastern Idaho, the soil must be wet at the time of the burn or shortly
fter the burn (Blaisdell 1953; Blaisdell and Mueggler 1956; Nord 1965). Otherwise,
ntelope bitterbrush seldom resprouts. If antelope bitterbrush plants do resprout,
hey will regain their original growth in 9 to 10 years (Blaisdell 1953). For a
urn in Idaho that was followed by several dry years, antelope bitterbrush was only
roducing 50 to 60 percent as much as the control 12 years after the burn (Blaisdell
953). The ability to resprout after pruning increases as the size and age of the
lant increases (Ferguson and Basile 1966; Ferguson 1968; Ferguson 1972).

Ecotypic variation would normally be expected within a wide-ranging species like
itterbrush. Ecotypes of antelope bitterbrush have been observed. Alderfer (1977)
ports three ecotypes in northern California and Oregon, a high elevation decumbent
orm, and two columnar forms. Monsen (1977, personal communications) has indicated
hree types occurring in Idaho, a low elevation decumbent form and two columnar forms,
ith one on granitic soils and the other on calcareous soils. In Utah, Plummer suggests
hat the decumbent and columnar forms represent at least two types.

The decumbent ecotype generally resprouts after fire or top removal. It is an
ggressive pioneer species capable of revegetating severely disturbed areas after
anting (Monsen and Christensen 1975). The columnar form on granitic soils in Idaho
ll also generally resprout after fire or top removal, but resprouting seems to be
ependent on fire intensity and soil moisture. The other ecotypes apparently are more
verely damaged by fire.

The decumbent life form is easily established from seed and is successfully used
r rangeland and logging road rehabilitation, particularly on well-drained, coarse-
xtured soils (Monsen and Christensen 1975). Because seeds must be cold treated and
arified (Young and Evans 1976b), the best time to burn for seed production is the
ll (Monsen and Christensen 1975). Abundant natural regeneration from seed caches
llowing fall burning has been reported by Klebenow and others (1976). Seedlings
om the low growing forms of antelope bitterbrush appear more competitive than do the
right forms (Monsen and Christensen 1975), and germination is high (Holmgren 1954).
wever, seedlings cannot compete with annual grasses during the first growing season
olmgren 1954).

Desert bitterbrush (*Purshia glandulosa*) usually resprouts after fire (Nord 1965). This species is closely related to antelope bitterbrush and the two interbreed (Monse and Christensen 1975) when their populations overlap. The amount of genetic variatio induced by interbreeding significantly affects both palatability and resprouting in antelope bitterbrush.

Tentative conclusions deduced from the data presented on antelope bitterbrush follow: (1) High-intensity wildfires during midsummer do the most damage to bitterbrush when the burning is followed by summer drought; under these conditions, most of the bitterbrush is killed. Cool spring burns in the decumbent ecotype(s) of bitterbrush result in low mortality and high resprouting; however, few seedlings establish i the burned area. Fall prescribed burns result in higher mortality than spring burns, but lower mortality than summer burns. If fall prescribed burns are conducted with favorable soil moisture conditions at the time of the burn or just after the burn, resprouting and layering occur in the decumbent ecotype. Reproduction from seed is highest following a fall burn. (2) Fire harms the columnar ecotypes more than it does the decumbent ecotypes. Cool fall fires are more important for the survival of antelope bitterbrush in the upright growth forms. (3) Fire harms bitterbrush more on fine-textured and calcareous soils than on coarse-textured and well-drained soils. Specific habitat and soils data are not available.

*Cliffrose*

Two varieties of cliffrose are recognized (*Cowania mexicana* var. *mexicana* and var *stansburiana*). Apparently, Stansbury's cliffrose is a strong sprouter and an aggressi pioneer species, whereas the mexicana cliffrose is a weak sprouter and not so aggressi Research on *Cowania mexicana* shows that it is generally killed by fire (Pechanec and others 1954; Vallentine 1971; Klebenow and others 1976). Like desert bitterbrush, cli rose interbreeds with antelope bitterbrush (Nord 1965; Sanderson 1969).

*Sagebrush*

Big sagebrush (*Artemisia tridentata*) is easily killed by fire (Blaisdell 1953; Pechanec and others 1954; Ralphs and others 1976). Blaisdell (1953) reports that big sagebrush does not resprout in southeastern Idaho, and repeated burning can almost completely eliminate sagebrush from a site (Pickford 1932). However, without repeated fires, sagebrush will reoccupy the burned area via seeding. Sagebrush can begin to reoccupy an area during the first year after the burn. Working at Dubois, Idaho, Blaisdell (1953) found that sagebrush in burned areas (12 years after the burn) was 10 percent of that in unburned areas, but had reached unburned levels in 30 years (Harniss and Murray 1973). Some areas recover more quickly if seed and moisture are available after burning (Pechanec and others 1954; Johnson and Payne 1968).

Mountain big sagebrush (*A. tridentata* ssp. *vaseyana*) recovers more quickly than other subspecies of big sagebrush perhaps because it occupies mesic sites and growing conditions are more favorable for seed production and reestablishment (Hironaka 1977, personal communication). Winward and Tisdale (1977) indicated that mountain big sageb shows a stronger tendency to increase in plant density and foliage cover in stands whe herbaceous vegetation is disturbed than basin big sagebrush (*A. tridentata* ssp. *triden* or Wyoming big sagebrush (*A. tridentata* ssp. *wyomingensis*). Basin big sagebrush norma occupies lowland plains and valleys on basic soils, whereas Wyoming big sagebrush occu drier valley and foothill sites (Plummer 1977). Though seed production is variable, d pending on soil moisture conditions, germination rates of all three subspecies of big sagebrush are high enough in all years to exclude seed germination as a limiting facto to reinvasion (Harniss and McDonough 1976).

High intensity wildfires leave few unburned plants and consume most seeds, which acounts for the variable establishment density of big sagebrush. Maximum spread of pogeny from parent plants of big sagebrush is 42 ft (12.8 m) (Frischknecht 1962), so wnd is evidently not a major factor in moving seed from adjacent unburned areas into brned areas. Normally, seeds of big sagebrush do not remain viable in the soil or ltter for more than 3 to 5 years (Monsen 1977, personal communication).

Other important related species are the lower growing black sagebrush (*A. nova*), lw sagebrush (*A. .arbuscula*), silver sagebrush (*A. cana*), and threetip sagebrush (*A. tipartita*). Fires rarely occur in the black and low sagebrush types. These shrubs gow in areas of shallow and droughty soils where production of herbaceous plants is oten inadequate to support a fire. Black and low sagebrush can reproduce by seed ater a fire but do not resprout. Three-tip sagebrush is a weak sprouter and silver sgebrush is a vigorous sprouter.

### *Rbbitbrush*

Rabbitbrush (*Chrysothamnus* sp.), a common genera in the sagebrush-grass region, is uually enhanced by fire (Cottam and Stewart 1940; Blaisdell 1953; Countryman and Crnelius 1957; Chadwick and Dalke 1965; Young and Evans 1974). An exception to this gneral response are two observations by Robertson and Cords (1957) for rubber rabbitbush (*Chrysothamnus nauseosus*). This species showed no recovery 2 years after a burn o September 3, 1942, near Mono Lake, Calif., and after a burn on November 7, 1943, nar McGill, Nevada. However, burning in the latter area was repeated on an unburned aea the following year on the same date and 95 percent of the plants resprouted. Eidently, the intensity of the fire is important because most of the sprouting after fre is epicormic (stem sprouting), not basal or root sprouting (Monsen 1977, personal cmmunication).

All varieties and subspecies of *Chrysothamnua viscidiflorus* resprout vigorously ad reseed well on disturbed areas (Plummer 1977). Seeds will carry long distances ad growth of seedlings is rapid.

For living plants that resprout, production is reduced for 1 to 3 years after burnig, then it increases dramatically (Blaisdell 1953). On the U.S. Sheep Station near Dpois, Idaho, burning reduced production 59 percent the first year after burning (laisdell 1953). Three years after burning, production doubled and was tripled at the ed of 12 years. Similarly, Chadwick and Dalke (1965) found that the cover of *C. vscidiflorus* had increased fourfold to ninefold on 8- to 18-year-old burns on sandy sils in northeastern Idaho. Production of *C. bloomeri* (*C. viscidiflorus*) doubled 5 yars after a burn in northern California (Countryman and Cornelius 1957). In western Nvada Young and Evans (1974) found that green rabbitbrush (*C. viscidiflorus* var. *vscidiflorus*) continued to dominate burns and reestablish itself periodically for 15 yars. Communities 40 to 50 years old were dominated by big sagebrush and contained rduced populations of green rabbitbrush.

### *Boom Snakeweed*

Broom snakeweed (*Gutierrezia sarothrae*) is a weak-sprouting perennial that is sverely damaged by fire (Pechanec and others 1954; Wright 1972). It may be completely rmoved from an area (Stanton 1974). New plants tend to invade open areas rapidly, and te highest frequencies of broom snakeweed are found on 22-year-old burns (Barney and Fischknecht 1974). Populations decline gradually for 50 years. On 100-year-old burns, ppulations are reduced to less than 10 percent (Barney and Frischknect 1974).

### *Hrsebrush*

Horsebrush (*Tetradymia canescens*) is a vigorous postfire sprouter that also rproduces abundantly from seed. Species of horsebrush cause liver damage to sheep, wth symptoms of photosensitization developing into severe poisoning (Kingsbury 1964).

Fire may reduce horsebrush by 50 percent the first year after a burn, but the specie doubles at the end of 3 years after a burn (Blaisdell 1953). Twelve years after thi same burn, horsebrush had increased fivefold. Thirty years after the burn many plants became decadent and began to die out (Harniss and Murray 1973). If fire or chemicals are used to treat decadent growth, horsebrush will become overwhelmingly dominant.

In addition to spineless horsebrush (*Tetradymia canescens*), littleleaf horsebru (*T. glabrata*) and catclaw or spiney horsebrush (*T. spinosa*) resprout after fire. However, littleleaf and catclaw horsebrush normally grow in drier sites in which the usually is not enough fuel to carry a fire (Hironaka 1977, personal communication). Hence, only spineless horsebrush is a potential problem following prescribed burning

### *Gambel Oak*

In Colorado, fire stimulates suckering of Gambel oak with a resultant thickenin and merging of stands into continuous thickets (Brown 1958). In Utah, McKell (1950) found that Gambel oak grew rapidly the first two growing seasons (50 percent recover after burning, but it had only recovered 75 percent of its original cover in 18 year after the burn (Wright 1972). The number of shoots increased after the fire and the declined until they were equal on both burned and unburned areas 18 years after the burn (Wright 1972). Oak tends to thin out and retreat when protected from fire (Bro 1958).

### *Snowberry*

After fire, common snowberry (*Symphoricarpos albus*) will resprout vigorously fr both rhizomes and basal buds. Creeping snowberry (*S. mollis*) is found in more mesic habitats. It is a weak sprouter after fire because its rhizomes, which may develop deep humus, are sometimes consumed or damaged in an intense fire (Stickney 1977, per sonal communication). Mountain snowberry (*S. oreophilus*) is found in drier habitats extending into sagebrush grass. It is a weak sprouter after fire. Pechanec and others (1954) and Blaisdell (1953) found that it decreased initially after burning although no further change was observed 12 years after burning.

Snowberry is capable of producing firebrand material. When snowberry is locate near fire control lines, it should be red-flagged as spot-fire.

### *Mountain-mahogany*

True mountain-mahogany (*Cercocarpus montanus*) is a vigorous sprouter after bein burned (Erdman 1970; Vallentine 1971). It is also highly palatable and of major imp tance in the Western United States (Medin 1960).

Curlleaf mountain-mahogany (*C. ledifolius*) is a weak sprouter after being burne but many of the resprouts die during the following two or three seasons (Monsen 1977 personal communication). Curlleaf is a slow-growing species, particularly as a seedling, but it can grow into a small tree (Dealy 1975). Few treelike curlleaf mountain-mahogany plants resprout after fire (Monsen 1977, personal communication).

### *Rose*

Several members of the rose family respond similarly to fire. Throughout their ranges serviceberry (*Amelanchier alnifolia*), oceanspray (*Holodiscus discolor*), nineb (*Physocarpus malvaceous*), bittercherry (*Prunus emarginata*), little-wild rose (*Rosa gymnocarpa*), woods rose (*Rosa woodsii*), and shiny-leaf spiraea (*Spiraea betulifolia*) resprout from a root crown. They resprout in habitats of subalpine fir (Lyon 1976), grand fir (Asherin 1973), cedar-hemlock (Mueggler 1965; Leege 1968), Douglas-fir (Ly 1971), ponderosa pine (Daubenmire and Daubenmire 1968), oak-brush (McKell 1950), nd sagebrush (Neuenschwander 1977, personal communication). Vegetative reproduction ollowing burning is the primary method of propagation. Reproduction from seed is arely observed after a burn. When seedlings are observed in a burn, their rate of rowth is slow compared to that of other species (Stickney 1977, personal communication).

### *erviceberry*

Serviceberry may be the most palatable browse species and the most fire sensitive ithin the rose family. At least two growth forms are recognized (Lonner 1972), with everal varieties. The most drought-tolerant variety, western serviceberry (*Amelanchier lnifolia* var. *utahensis*), is damaged by fire but it resprouts (Wright 1972; Stanton 974). The more mesic variety, common serviceberry (*A. alnifolia* var. *alnifolia*) also esprouts and is not severely harmed. Based on observations in southern Idaho and in tah, no mortality following wildfires has been recorded for Utah serviceberry (Monsen 977, personal communication). Apparently western serviceberry, which is a longlived pecies (Hemmer 1975), can remain suppressed in a closed stand of conifers or juniper or a long period of time. Canopy removal of the resident trees will stimulate resprout-ng (Lyon 1971; Asherin 1973).

### *eanothus*

Most seeds of *Ceanothus* can withstand high external temperatures and maintain ermination capabilities (Biswell 1974). Snowbrush (*C. velutinus*) and redstem eanothus (*C. sanguineus*) seeds require heat scarification before they will germinate Lyon 1976). In addition, they resprout after fire. Sprouting may be considered an daptation to recurring fires (Biswell 1974) because of the rapid growth and recovery fter fire. Thus, *Ceanothus* is well adapted to fire for two reasons: (1) many of the hrubs resprout after fire; and (2) seeds, which are produced at an early age, may lie ormant and viable in the duff and soil for extremely long periods of time, and are ighly resistant to fire. Seedlings are usually abundant after fire.

When Leege (1968) compared spring burns to fall burns to rejuvenate redstem eanothus, spring burns were found to produce fewer resprouts than fall burns, and few eedlings of redstem ceanothus were alive by the end of the second growing season fter the burn. However, many seedlings of redstem ceanothus survived the fall burn. eege's study findings, if applicable to other species of *Ceanothus*, may imply that pring burning could potentially harm the species that reproduce primarily by seed. uccess in regeneration and rejuvenation of *Ceanothus* following spring burning is xtremely variable, presumably, due to the variation in duff moisture and fire intensity. owever, spring burns do not require the fire control effort of fall burns, therefore pring burns are more economical. Late summer or fall burns, however, do increase he numbers of young plants and resprouts.

## Response of Pinyon and Juniper to Burning

### *inyon and Juniper*

The effect of fire on pinyon and nonsprouting juniper trees depends largely upon he height of trees, herbaceous fuel, weather conditions, and season. In open pinyon-uniper stands with an understory of 700 to 1,000 lb/acre (786 to 1,123 kg/ha) of fine uel, Jameson (1962) and Dwyer and Pieper (1967) found that pinyon and juniper were asily killed by spring fires if less than 4 ft (1.2 m) tall when air temperature was 0° to 74°F (21° to 23°C), relative humidity 20 to 40 percent, and windspeed was 10 to 0 mi/h (16 to 32 km/h). Lower air temperatures in January [49° to 54°F (9° to 13°C)], relative humidity of 44 percent, and windspeed of 6 to 8 mi/h (10 to 13 km/h) caused very spotty burn in which crown kill varied from 30 to 70 percent for trees 2 to 4 ft 0.6 to 1.2 m) tall, but 70 percent of the trees eventually died (Jameson 1962).

A wildfire in June, with an air temperature of 97°F (36°C), windspeed of 10 to 15 mi (16 to 24 km/h), and relative humidity 17 to 25 percent assured a 100 percent kill o all trees less than 4 ft (1.2 m) tall, but was no more effective on taller trees tha when air temperatures were 70° to 74°F (21° to 23°C) (Jameson 1962).

Trees greater than 4 ft (1.2 m) tall in open pinyon-juniper stands are difficul to kill unless you have heavy accumulations of fine fuel beneath the trees. On the wildfire studied by Dwyer and Pieper (1967), only 24 percent of the pinyon and 13.5 percent of the juniper that exceeded 4 ft (1.2 m) tall died. Jameson (1962) found t most juniper over 4 ft (1.2 m) tall only had a 30 to 40 percent crown kill, unless tumbleweeds had accumulated at the base of the trees. Then 60 to 90 percent of the crowns were killed, particularly for trees 8 to 10 ft (2.4 to 3.0 m) tall. East of pinyon-juniper zone in Texas, juniper trees up to 12 ft (3.7 m) tall were easily kil when fine fuel was 2,000 lb/acre (610 kg/ha) or higher (Wink and Wright 1973).

Trees in closed stands (no grass or shrubs in the understory) of pinyon-juniper are difficult to kill because fires will not spread readily (Arnold and others 1964; Blackburn and Bruner 1975). Dense stands [495 to 988 trees/acre (1,222 to 2,440 tre ha)] in 14- to 18-inch (35- to 45-cm) rainfall areas with a mixture of pinyon and juniper can be burned on hot days, but pure stands of juniper are almost impossible burn (Blackburn and Bruner 1975). A number of people in the Great Basin area specul that it would require windspeeds exceeding 35 mi/h (56 km/h) to burn pure stands of juniper. Thus, many attempts to burn such stands have failed (Arnold and others 196 Aro 1971). As the proportion of pinyon to juniper increases and the density increas the stands are easier to burn (Truesdell 1969; Blackburn and Bruner 1975). Such area are usually burned by clearing an area 20 to 125 ft (6.1 to 3.8 m) wide and pushing windrow against the green trees on the windward side and letting the material cure f 60 to 90 days. Then in June or July, burns are conducted when temperatures vary fro 80° to 95°F (27° to 35°C), relative humidity is 4 to 8 percent, and windspeeds excee 8 mi/h (13 km/h) (Truesdell 1969; Blackburn and Bruner 1975). These burns have been conducted on mesas or next to the Grand Canyon where firebrands are not a problem.

A mixture of sagebrush and pinyon-juniper is common throughout the Great Basin, and it is feasible to burn and kill large pinyon and juniper trees in these communit (Bruner and Klebenow (1979). To get a fire to carry, Bruner and Klebenow (1979) hav proposed the "White Pine County Formula" where,

Index = Maximum wind (mi/h) + Shrub and tree cover (%) + Air temperature (°F).

If the index is 110 or higher a fire will carry and will kill the large pinyon and juniper trees. If the index is above 130, it is too dangerous to burn. Most of the work by Bruner and Klebenow has been done in pinyon-juniper stands with 45 to 60 percent of shrub and tree cover and burned when air temperature was 60° to 75°F (16° to 24°C), relative humidity was below 25 percent, and maximum windspeed was 5 to 25 mi/h (8 to 40 km/h).

Alligator juniper and redberry juniper are the only sprouting junipers. Smith others (1975) found that if the tops of redberry juniper trees were removed before th reached 12 years of age, 99 percent mortality could be expected. Older trees were not studied. This data implies that if burned every 10 years or so, sprouting species of juniper may have a difficult time invading grasslands. Schroeder (1956) found that about 40 percent of alligator juniper trees less than 15 ft (4.6 m) tall could be kill by burning individual plants.

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Table 2.--*Summary of fire effects on major grass and grasslike species*

| Species | Response to fire | Recovery time | Remarks |
|---|---|---|---|
| | | *Years* | |
| Bluegrass | | | The bluegrasses are generally small plants and fire damage is minimal with late summer and fall burns. |
| Big | Slight damage | 1-3 | |
| Cusick | Slight damage | 1-3 | |
| Nevada | Slight damage | 1-3 | |
| Sandberg | Undamaged | 1-3 | |
| Cheatgrass | Undamaged | 1 | Any reduction in cheatgrass stands is usually short-lived. |
| Idaho fescue | Slight to severe damage | 2-30 | Spring or fall burning with adequate soil moisture appears to damage plants only slightly, but this species can be seriously harmed by hot summer or fall fires, particularly where precipitation is marginal for the existence of this species. |
| Indian ricegrass | Slight damage | 2-4 | Good resistance to burning but slow to increase in density. |
| Junegrass | Undamaged | 1-3 | Probably increase in density for several years after burning. |
| Needlegrass | | | Needlegrasses are generally the least fire-resistant bunchgrasses. Large plants are damaged more than small plants. A 50 percent reduction in basal area should be anticipated among the various size plants in a given area. |
| Columbia | Moderate damage | 3-5 | |
| Needle-and-thread | Severe damage | 4-8 | |
| Thurber | Severe damage | 4-8 | |
| Western | Moderate damage | 3-5 | |
| Plains reedgrass | Undamaged | 1-2 | Rhizomatous species that is fire resistant. |
| Sedges | | | |
| Douglas | Undamaged | 1-3 | |
| Threadleaf | Severe damage | 4-10 | |
| Bottlebrush squirreltail | Slight damage | 1-3 | One of the most fire-resistant bunchgrasses, although burning in a dry year can reduce basal area. Bottlebrush squirreltail can increase several years after burning. |
| Wheatgrass | | | Bluebunch wheatgrass can be damaged if burned in a dry year. Other wheatgrasses are difficult to burn in seeded monocultures. |
| Bluebunch | Slight damage | 1-3 | |
| Crested | Undamaged | 1-2 | |
| Intermediate | Undamaged | 1-2 | |
| Pubescent | Undamaged | 1-2 | |
| Riparian | Undamaged | 1-2 | |
| Tall | Undamaged | 1-2 | |
| Thickspike | Undamaged | 1-2 | |
| Western | Undamaged | 1-2 | |

Table 3.--*Response of cold desert forbs to fall burning*

| Severely damaged | Slightly damaged | Undamaged |
|---|---|---|
| Hairy fleabane | Astragalus | Arrowleaf balsamroot |
| Hoary phlox | Matroot | Common comandra |
| Littleleaf pussytoes | Munro globemallow | Common sunflower |
| Low pussytoes | Northwestern paintbrush | Coyote tobacco |
| Mat eriogonum | Pinnate tansymustard | Douglas knotweed |
| Uinta sandwort | Plumeweed | Flaxleaf plainsmustard |
| Wyeth eriogonum | Red globemallow | Flixweed tansymustard |
|  | Sticky geranium | Foothill deathcamas |
|  | Tailcup lupine | Gayophytum |
|  | Tapertip hawksbeard | Goldenrod |
|  | Tongueleaf violet | Goosefoot |
|  | Tumblemustard | Lambstongue groundsel |
|  | Wavyleaf thistle | Longleaf phlox |
|  | Whitlow-wart | Orange arnica |
|  | Wild lettuce | Pale alyssum |
|  |  | Purpledaisy fleabane |
|  |  | Russian thistle |
|  |  | Velvet lupine |
|  |  | Western yarrow |
|  |  | Wild onion |

Table 4.--Summary of fire effects on major shrub species in the juniper forest and sagebrush grass zones of the Intermountain region

| Species | Sprouting ability | Response to fire | Recovery time | Remarks |
|---|---|---|---|---|
|  |  |  | Years |  |
| Antelope bitterbrush | Weak sprouter | Severely damaged by summer and fall burns | 30-40 | Effect determined by growth form; decumbent form sprouts vigorously, columnar form is a weak sprouter. If plants sprout, they will recover in 9 to 10 years. Spring burns enhance sprouting but fall burns are best for reproduction from seed. Burn when soil is wet. |
| Desert bitterbrush | Sprouter | Unharmed |  |  |
| Cliffrose | Weak to nonsprouter | Usually killed by fire |  |  |
| Big sagebrush | Nonsprouter | Severely harmed | 30 | Good seed crop before burning hastens recovery. Effective control requires burning before seed-set and periodic burns. May use black and low sage as fuel breaks. Subspecies of big-sagebrush appear to be important relative to response to burning. |
| Black-sagebrush | Nonsprouter | Rarely burned |  |  |
| Low sagebrush | Nonsprouter | Rarely burned |  |  |
| Silver sagebrush | Sprouter | Slightly harmed |  |  |
| Three-tip sagebrush | Weak sprouter | Harmed | 30 |  |
| Rubber rabbitbrush | Vigorous sprouter | Enhanced | 20-25 | May be killed if burned after heavy grazing or burned in early summer. |
| Green rabbitbrush | Vigorous sprouter | Enhanced | 20-25 |  |
| Broom snakeweed | Weak sprouter | Severely harmed | 20-25 | Rapid recovery. |
| Horsebrush | Vigorous sprouter | Enhanced | 30-35 | Toxic, increases fivefold within 12 years. |
| Gambel oak | Vigorous sprouter | Enhanced | 30-40 |  |
| Common snowberry | Vigorous sprouter | Unharmed | 10 | Enhanced by cool fires but harmed by hot fires. |
| Mountain snowberry | Sprouter | Slightly harmed | 15 |  |
| Mountain-mahogany | Sprouter | Slightly harmed | Recovery times not available in literature. | More information is needed. |
| Western mahogany | Sprouter | Slightly harmed |  |  |
| Curlleaf mahogany | Sprouter | Moderately harmed |  |  |
| Serviceberry | Sprouter | Slightly harmed | 30-50 | Highly adapted to fire; soil being moist at the time of the burn is important. Usually poor reproduction from seed. |
| Ocean-spray | Sprouter | Enhanced | 20-30 |  |
| Ninebark | Sprouter | Enhanced | 20-30 |  |
| Bittercherry | Sprouter | Unharmed | 30-40 |  |
| Rose | Sprouter | Enhanced | 15-30 |  |
| Spireaea | Sprouter | Unharmed | 20-30 |  |
| Ceanothus |  |  |  |  |
| Nonsprouting group | Nonsprouters | Harmed by spring | Recovery times not available in literature. | Seedling are enhanced with fall burns. |
| Sprouting group | Vigorous sprouters | Unharmed to enhanced |  |  |

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Wright, Henry A., Neunschwander, Leon F., and Britton, Carlton M.
1979. The role and use of fire in sagebrush-grass and pinyon-juniper plant communities. A state-of-the-art review. USDA For. Serv. Gen. Tech. Rep. INT-58, 48 p. Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.

Summarizes current knowledge of the effects of fire on vegetation in sagebrush-grass and pinyon-juniper communities. For the convenience of the reader, data are presented from an ecological perspective and by individual species. Includes sections on prescribed burning, management implications, and state-of-the-art knowledge for sagebrush-grass and pinyon-juniper vegetative types.

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# CHRONOLOGY AND CHARACTERISTICS OF A DOUGLAS-FIR BEETLE OUTBREAK IN NORTHERN IDAHO

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INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE

FRONT COVER:

A group of trees killed by the
Douglas-fir beetle in the
Clearwater drainage.

USDA Forest Service
General Technical Report INT-59
September 1979

# CHRONOLOGY AND CHARACTERISTICS OF A DOUGLAS-FIR BEETLE OUTBREAK IN NORTHERN IDAHO

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# PREFACE

We hope that this account will provide technology and data for others who would seek to measure and describe future outbreaks of the Douglas-fir beetle in the Northern Rocky Mountains.

Our chronology began in 1971, two generations after beetles are thought to have bred to abundance in trees felled during clearing for Dworshak Reservoir. We entered the scene after standing trees were reported to be dying and continued the study until 1974 when the infestation waned. More recently, we have begun sampling infested and green stands, seeking to relate their characteristics to beetle susceptibility. Results of this work will be reported separately.

# RESEARCH SUMMARY

A Douglas-fir beetle infestation that killed 111 million bd.ft. of sawtimber was studied over a 4-year period to determine factors associated with its occurrence and decline. Occurrence of the outbreak was associated with felled and damaged trees, dense stands of Douglas-fir, predominantly on good sites, and possibly root rots of which *Verticicladiella wagnerii* Kendrick was found in Douglas-fir for the first time. Tree mortality began declining during the third year of the infestation, accompanied by increased resistance of trees to attack; a beetle population index of 1.1 in the fall; and a higher proportion of immature overwintering brood. A verbal model is proposed to describe the functioning of factors that regulate beetle populations and damage. Preventive measures are suggested.

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# INTRODUCTION

The Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopk., infests mainly Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, in which it periodically reaches epidemic levels (Furniss and Orr 1970). Historically, outbreaks in coastal areas have been attributed to catastrophic disturbances, especially windthrow. Relationships involving outbreaks in Rocky Mountain areas seem more diverse than elsewhere and have not been well documented and reported.

Study of Rocky Mountain infestations has been difficult due to lack of accurate, quantitative measurements of tree damage to which causal factors could be related. Detection of infested trees for damage measurement and population sampling is complicated by the time lag between beetle attack and reddening (fading) of foliage. Rate of fading varies considerably among trees and between years (Belluschi and Johnson 1968), probably influenced by attack density and moisture stress. Infested trees occur in groups, which contributes to variation between randomly distributed sample plots. Within individual trees, attacks are located so high that samples must be taken 10 ft or more above ground with a ladder or tree climbing device (Furniss 1962a).

Discovery of an outbreak in the Clearwater drainage of northern Idaho provided an opportunity to investigate factors involved with infestation trends. Biological studies were conducted with others who were seeking to develop and apply a photographic method to measure tree mortality (Ciesla and others 1971). The objective was to look for relationships among trend of tree mortality and factors involving insect populations and suceptibility of individual trees and stands. When understood, these relationships would be useful for predicting outbreaks.

# BACKGROUND

In 1969 an outbreak of Douglas-fir beetles developed in the North Fork Clearwater River drainage. The beetles may have bred to epidemic levels in trees felled during clearing for Dworshak Reservoir and in snow-broken Douglas-fir surrounding the reservoir (Ciesla and others 1971). The previous Douglas-fir beetle outbreak in the Clearwater River drainage occurred in 1950-1952.[1] During those years, 7.6 percent of the merchantable Douglas-fir had been killed.

Severity of this most recent outbreak became evident in spring 1971 when foliage of infested trees turned red.[2] The damage occurred within approximately 270,000 acres of forest. Some infested trees were only 80 to 90 years old--much younger than we had encountered previously. Alarmed by this damage, members of the Northern Rockies Forest Pest Action Council undertook a cooperative survey of tree mortality by aerial photography and ground sampling to assist salvage logging operations.

---

[1] Evenden, James C. Nov. 1952. Douglas-fir infestation, Northern Rocky Mountain Region. For. Insect Lab., Coeur d'Alene, Idaho, unpubl. rep., 9 p.

[2] Koppang, M. D. Clearwater-Potlatch Timber Protective Association, Orofino, Idaho, July 1, 1971, personal communication.

Although the outbreak had already been underway for 2 years, we decided to observe and sample the beetle population and associated factors until the infestation subsided; something never reported before in the Northern Rocky Mountains. This paper presents findings after observing four generations of beetles. We include information obtained in separate cooperative surveys of infested trees (Ciesla and others 1971; McGregor and others 1972; McGregor and others 1974).

# METHODS

The area studied lies within the North Fork Clearwater River drainage between Elk Creek and the Little North Fork (fig. 1).

Trend of damage was determined from estimates of numbers and volumes of infested trees obtained from aerial photos and ground sampling. Beetle populations were measure on bark samples from infested trees. Other data were taken from individual infested trees and stands.

## Damage

### 1971

The number and volume of infested trees on 288,000 acres were estimated by interpreting 100, 100-acre aerial photo plots and cruising 26 of these plots (Ciesla and others 1971). Plots were photographed in mid-August on a 9-inch format at a scale of 1:7,920 on Ektachrome infrared Aero (8443) film. The camera for this and subsequent photography was a Zeiss-RMKA 15-23 equipped with a 6-inch focal length lens and anti-vignetting color filter.

### 1972

The procedure was essentially the same as in 1971, except that 161, 100-acre photo plots were taken in mid-July on true color film (Kodak SO 397) to sample a larger area totaling 494,080 acres (McGregor and others 1972). Twenty-four plots were sampled by ground crews to obtain factors with which to correct photo interpretations of damage.

### 1973

In late July, 287,000 acres were surveyed by 186, 100-acre photo plots using color Ektachrome MS Aerographic 2448 Estar Base film. Thirty, 100-acre plots were selected for ground cruising to correct aerial photo interpretations and estimate damage (McGregor and others 1974). Faded trees were counted on each 100-acre photo plot, and a dot-grid was used to determine areas of merchantable forest as opposed to other areas. This stratification eliminated from the survey nonhost types as well as nonsusceptible younger age classes, such as pole stands and nonstocked areas.

### 1974

Because of decline of the outbreak and other commitments, aerial photography and ground surveys were discontinued. Instead, faded (1973-attacked) groups were observed and mapped from aircraft during August 12-13. Trees that were infested in 1974 were sought on the ground in August when sampling began. Such trees were scarce and difficult to identify so soon after being infested.

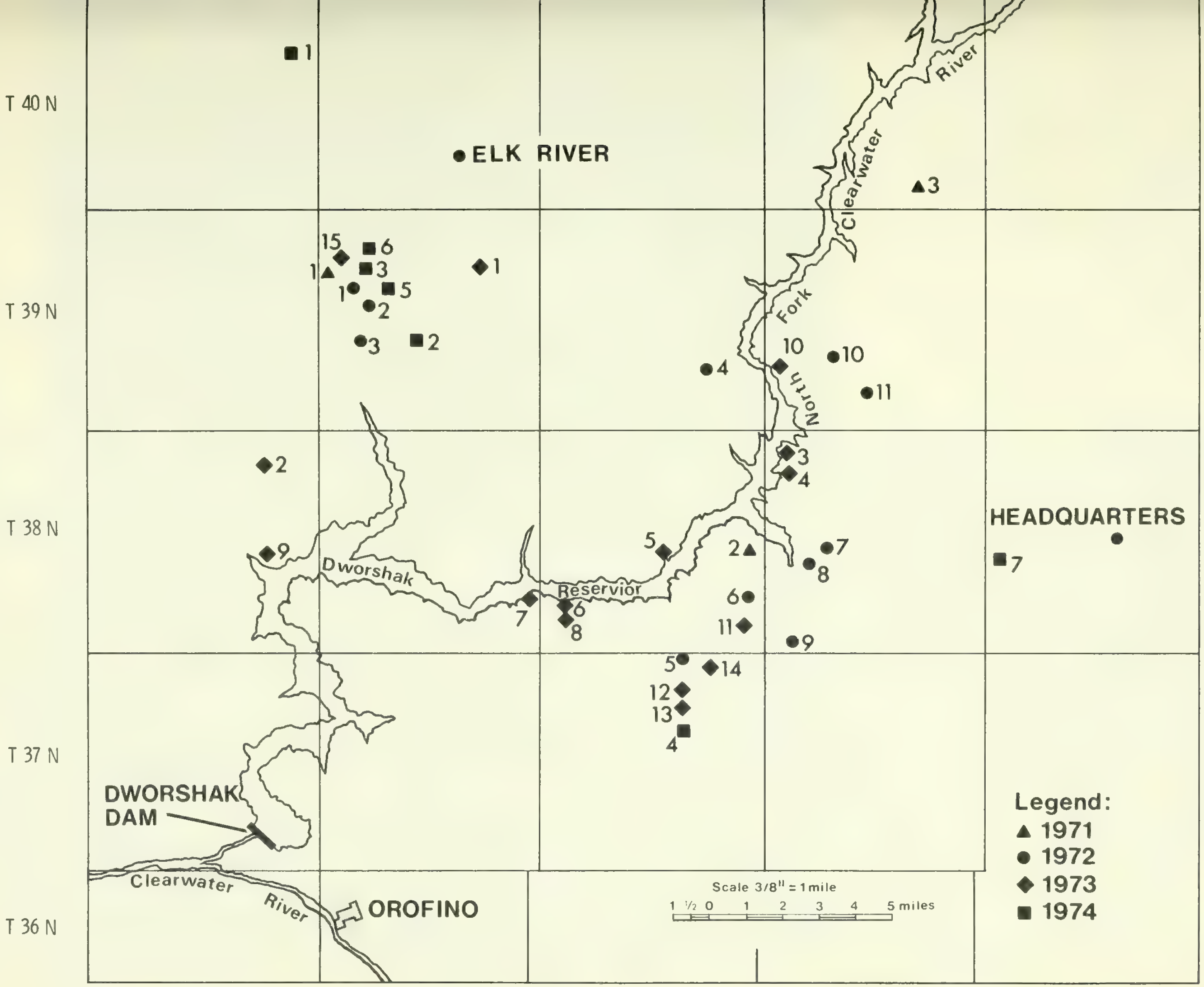


Figure 1.--Study area and location of sample groups of infested trees.

# Population and Other Factors

## THIRD GENERATION OF OUTBREAK (1971)

During October 27-November 1, 1971, we examined three infested groups of trees. All trees (468 total) in these groups were rated for success of beetle attack, and the diameters at breast height (d.b.h.) were measured. The percentage of trees attacked unsuccessfully (fig. 2A) was computed to indicate the importance of tree resistance i the eventual decline of the infestation.

Then, from each group 20 successfully attacked trees--trees in which the brood s vived at least to larval stage--fig. 2B) were selected randomly from among all diamet classes. From each of these trees, two bark samples (1/10 ft$^2$ each) were removed fro a height of ca 12 ft above ground (fig. 3A,B). The sampling punch and the distributi of Douglas-fir beetle attacks in standing trees have been described (Furniss 1962a,b) An 8-foot ladder was necessary to reach 10 ft or higher, where attacks are more unifo and representative of infestation in the tree.

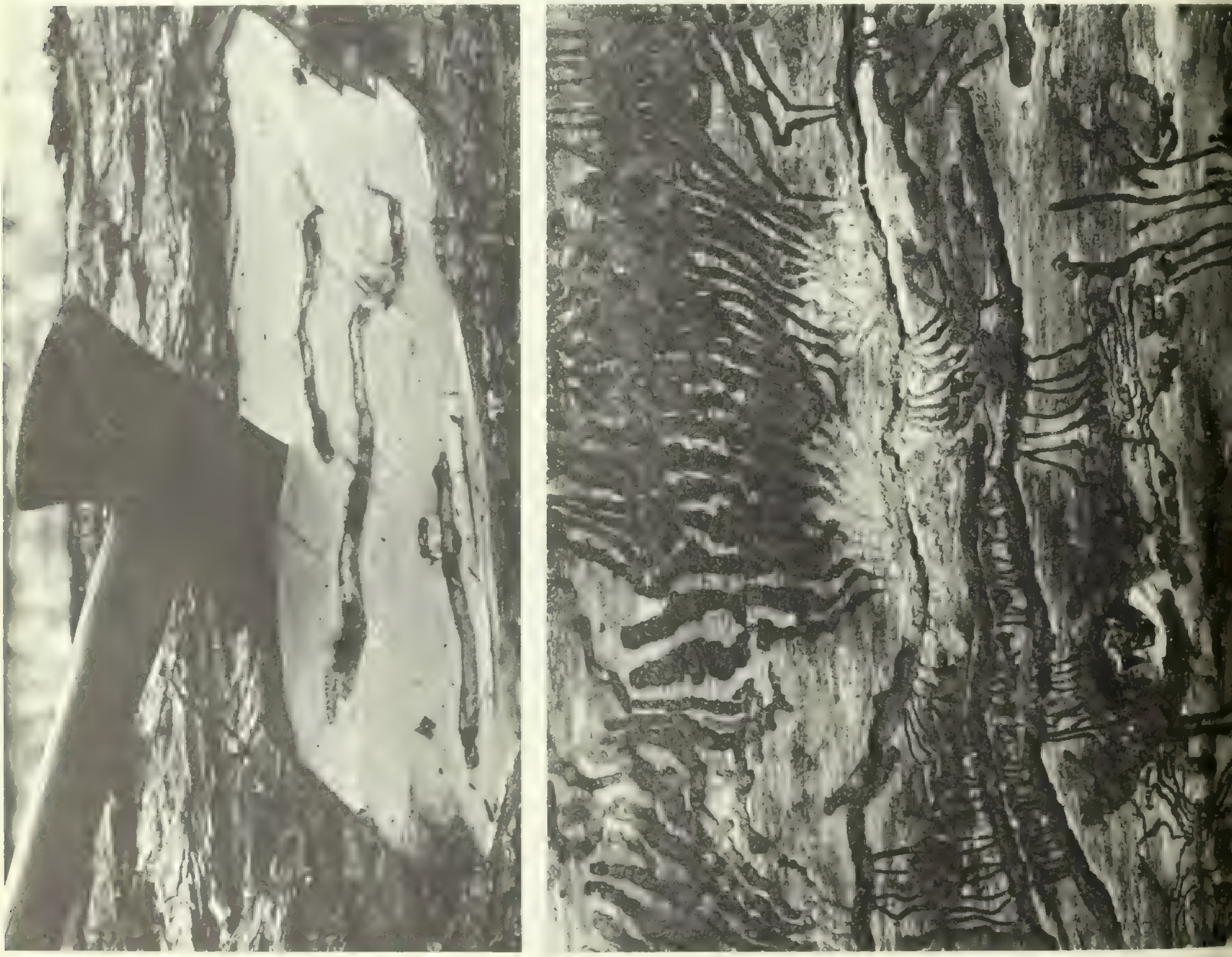
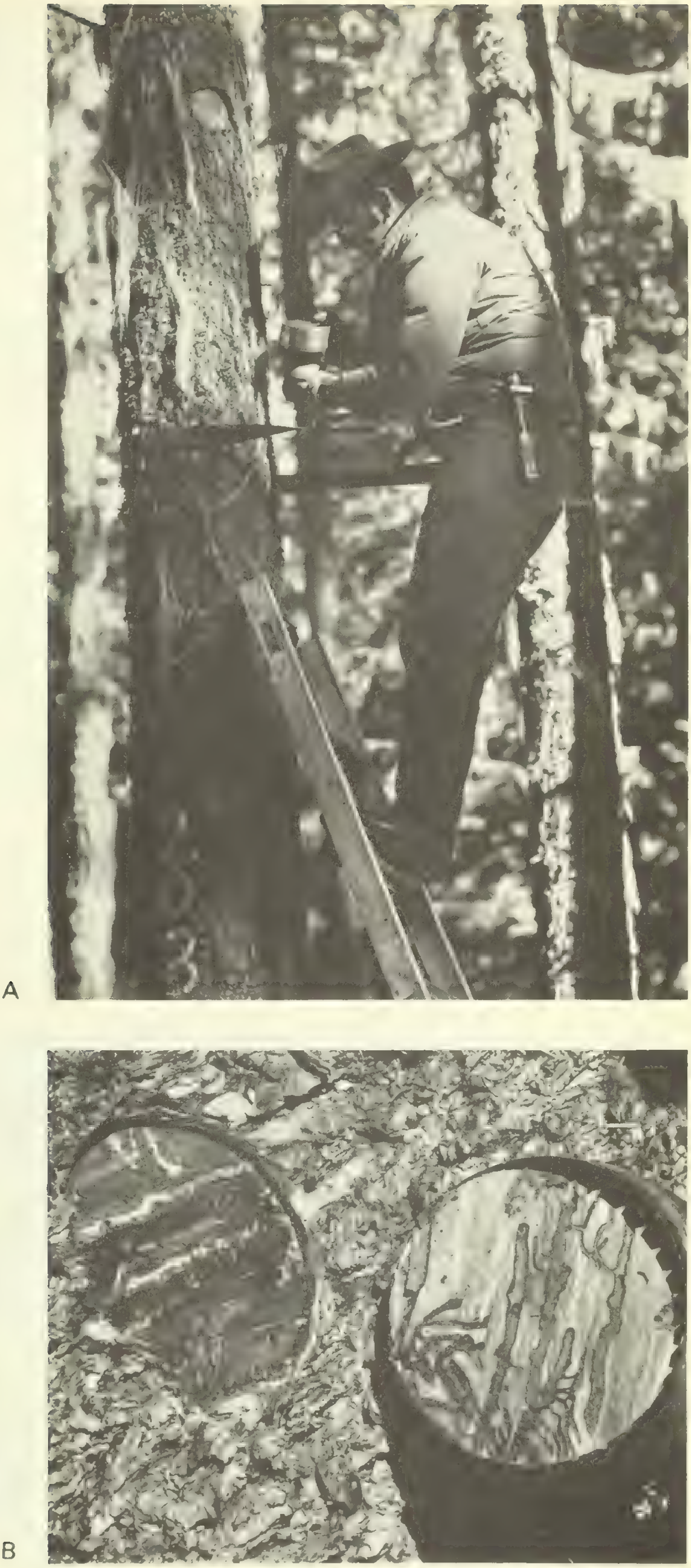


Figure 2.--A. Beetle galleries in a tree that survived attack. Such galleries produced no live brood. B. Successful galleries and larval mines in a killed tree.

igure 3.--A. Population trend and abundance of predators and parasites were determined from bark samples taken with a circular punch 10 to 12 ft above ground. B. Bark sample containing Douglas-fir beetle egg galleries and larval mines.



We counted numbers of gallery starts (attacks), Douglas-fir beetle brood by stages and immature parasites and predators by species. A Douglas-fir beetle population trend index (ratio of brood to attacking parents) was computed to relate to damage trend. Sample trees were then divided into categories of population trend. Those having a ratio of brood/parents >1 were designated "population generators" and those <1 were designated "population sinks."

## FOURTH GENERATION OF OUTBREAK (1972)

Because we thought that the three large groups sampled in 1971 might be biased in size and too few in number, we sought a more representative sample in 1972. But infest trees were still green in appearance and difficult to find. To improve our search technique we tried the following procedures.

We sought to determine the closest distance between faded groups that appeared on aerial photo pairs taken in 1971 and 1972 (fig. 4). That is, we looked for a group tha appeared on both years' photos; and another group that appeared only on the later photo of each pair. We intended to begin searching for 1972-infested trees (most were still green) at a radius of the minimum distance between groups of previous years. However, only five photo pairs covered the same ground area both years, and none had more than one year's group on it. Thus, beetles were shown to have flown from the group of their origin to distances beyond the scope of the photos. We think that this method might have worked earlier in the outbreak when infested groups were more abundant and therefore closer together.

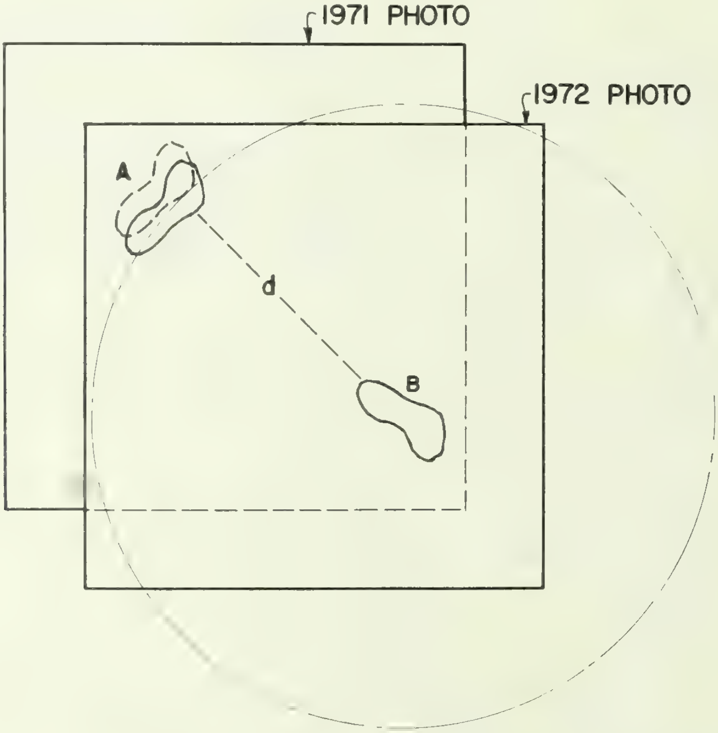


Figure 4.--Conceptual illustration of attempted method of sampling 1972-attacked trees. A is the same group visible on photos taken in 1971 and 1972. B is a group visible only on 1972 photos. Distance "d" between groups is the radius of search for 1972-attacked trees (still green) for comparative sampling.

Eventually, 11 groups were located after much searching and were sampled during September 5-October 6, 1972. Procedures during this sampling were similar to those in 1971, except that additional data were obtained including (1) physiographic features (elevation, aspect, and topographic position) and (2) presence of vegetation indicative of moistness and dryness. Moist sites were identified by grand fir; dry sites by grass or snowberry; and intermediate moisture conditions by ninebark or oceanspray (Daubenmire and Daubenmire 1968).

We also examined four groups (two 1971- and two 1972-attacked) and inventoried all trees greater than 7.6 inches d.b.h. within the perimeter of each group. From this inventory we calculated the proportion of Douglas-fir, the density of stems, and the basal area per acre. Because no local Douglas-fir stocking or yield table was available, we used yield tables for second-growth western white pine (Haig 1932), which occurred in parts of the study area. We referred to Deitschman and Green (1965) to relate heights of dominant Douglas-firs to white pine site index, from which we determined normal stocking. Site index was determined by measuring height and age of about 10 trees per group (Brickell 1968). Habitat type (Daubenmire and Daubenmire 1968) and soil depth were also determined.

We also tallied understory trees (less than 7.6 inches d.b.h.), by species, on ten 4-milacre quadrats per group. The quadrats were located randomly along lines at 50-ft intervals across the length of each group.

We checked the accuracy of previous ground estimates of success of attacks by examining beetle galleries higher in the trees with the aid of a ladder. Root rots were evaluated by falling six trees in two of the groups. These trees were chosen to represent extremes of beetle infestation and included both successfully attacked and unsuccessfully attacked trees. Then the soil around the roots was excavated by blasting (fig. 5). Kinds of rots were determined symptomatically by examining the exposed roots.

## FIFTH AND SIXTH GENERATIONS OF OUTBREAK

In 1973, we located 15 groups of infested trees while they still appeared to be normal. However, because of a decline in the outbreak, we located only seven currently infested groups in 1974. All groups were inventoried and sampled by procedures used previously.

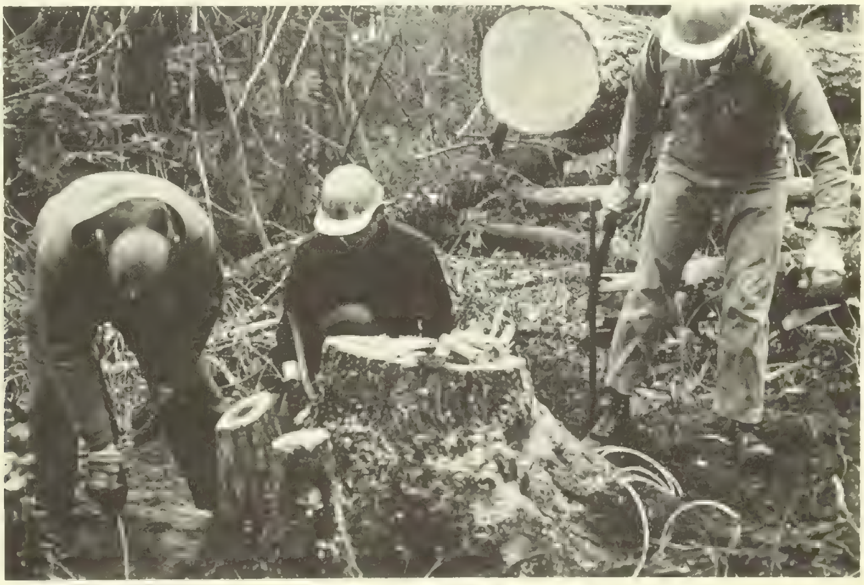


Figure 5.--Preparation for blasting to excavate dirt from roots to enable diagnosis of root rot infection.

# RESULTS AND DISCUSSION

## Damage Measurement

Volume of Douglas-fir killed during 1971-1974 was approximately 111 million bd.ft. or about 15.3 percent of the merchantable Douglas-fir stand (McGregor and others 1974; Hamel and others 1975). The damage trend during those years is shown in figure 6.

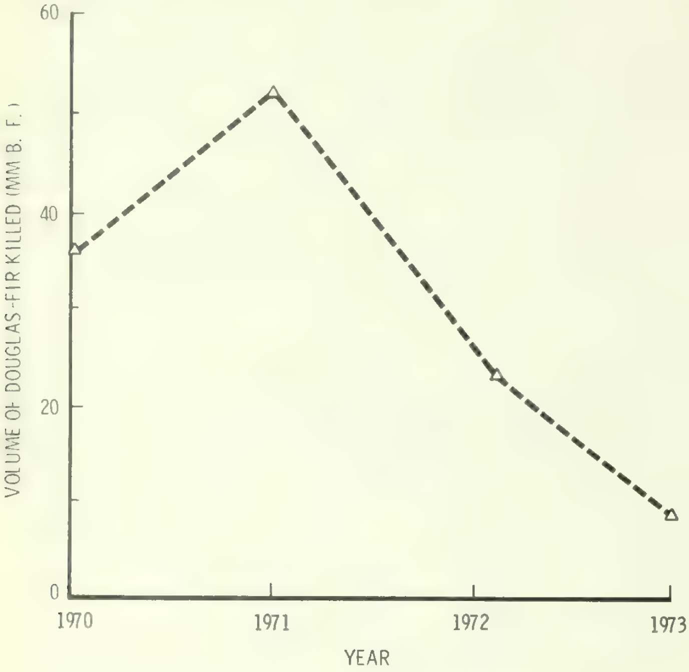


Figure 6.--Trend of Douglas-fir beetle infestation expressed in millions of board feet of Douglas-fir stand killed, 1970-1973.

## Population and Other Factors

### THIRD GENERATION OF OUTBREAK (1971)

*Characteristics of attacked trees and groups.*--The infested groups were large, averaging 158 trees (table 1). Such large groups were characteristic of those visible during the first two generations of the outbreak.[2] Average age of attacked trees was 9 years (R = 71-135). In the Rocky Mountains trees younger than 100 years seldom have be infested.

Examination of galleries disclosed that 31 percent of the trees appeared to have been attacked unsuccessfully. However, we re-examined two of these groups a year later and found that 14 percent of the trees originally classed as "unsuccessful" had, in fact, been killed (table 2). The error resulted from originally determining success of attack from the ground; while in checking accuracy, we used an 8-ft ladder to reach a height of 10 to 12 ft. Attacks were significantly more dense and successful above the height we could easily reach from the ground (Furniss 1962a). Later, a similar error (11 percent) was determined for two 1972-infested groups, so we think the 27 percent (58-31=27) increase in unsuccessful attacks between 1971 and 1972 (table 1) was not the result of errors in rating success of attack between the 2 years but was a real increas in resistance.

Table 1.--*Characteristics of sample groups of trees attacked by Douglas-fir beetles, 1971-1974*

| Group | Age | Height | Number | Percent unsuccessful | D.b.h. | |
|---|---|---|---|---|---|---|
| | | | | | unsuccessful | successful |
| | | *Feet* | | | - - - - - - -*Inches* - - - - - - | |
| | | | | 1971 | | |
| 1 | 106 | -- | 113 | 26 (15)[1] | 16.3 (15.7) | 17.6 (17.5) |
| 2 | 95 | -- | 180 (187) | 39 (22) | 17.4 (14.8) | 19.8 (20.0) |
| 3 | 88 | -- | 175 | 26 | 16.4 | 18.4 |
| Average | 97 | -- | 158 | 31 (22) | 16.7 (15.6) | 18.7 (18.8) |
| | | | | 1972 | | |
| 1 | 120 | -- | 114 | 66 (53) | 17.0 (17.3) | 19.0 (19.0) |
| 2 | 118 | 114 | 20 | 75 | 19.7 | 16.6 |
| 3 | 91 | 106 | 266 | 68 | 18.0 | 17.4 |
| 4 | 164 | 133 | 14 | 50 | 23.9 | 30.7 |
| 5 | 120 | 124 | 48 | 67 | 17.9 | 21.0 |
| 6 | 116 | 111 | 68 | 38 (29) | 19.1 (20.9) | 23.2 (23.0) |
| 7 | 127 | 134 | 17 | 65 | 25.1 | 24.9 |
| 8 | 144 | 102 | 149 | 45 | 16.5 | 16.9 |
| 9 | 154 | 113 | 26 | 38 | 22.7 | 25.2 |
| 10 | 95 | 111 | 133 | 65 | 16.8 | 16.8 |
| 11 | 94 | 116 | 18 | 83 | 20.4 | 22.0 |
| Average | 118 | 116 | 79 | 58 | 18.0 | 19.1 |
| | | | | 1973 | | |
| 1 | 172 | 122 | 7 | 43 | 21.2 | 24.5 |
| 2 | 144 | 108 | 10 | 80 | 17.5 | 18.3 |
| 3 | 92 | 109 | 5 | 0 | -- | 18.3 |
| 4 | 145 | 134 | 27 | 8 | 22.2 | 27.3 |
| 5 | 146 | 140 | 12 | 17 | 22.4 | 29.3 |
| 6 | 122 | 127 | 15 | 7 | 24.0 | 24.9 |
| 7 | 127 | 120 | 15 | 73 | 19.3 | 23.4 |
| 8 | 149 | 128 | 6 | 0 | -- | 24.0 |
| 9 | 89 | 110 | 14 | 29 | 12.0 | 22.9 |
| 10 | 116 | 106 | 21 | 38 | 14.5 | 19.9 |
| 11 | -- | 102 | 20 | 5 | 11.0 | 19.2 |
| 12 | 78 | 114 | 17 | 6 | 18.2 | 16.9 |
| 13 | 83 | 92 | 11 | 9 | 17.3 | 17.2 |
| 14 | 95 | 97 | 117 | 35 | 14.1 | 19.2 |
| 15 | 94 | 128 | 29 | 38 | 17.2 | 19.6 |
| Average | 117 | 113 | 22 | 29 | 16.0 | 21.1 |
| | | | | 1974 | | |
| 1 | 110 | 107 | 27 | 52 | 18.8 | 19.8 |
| 2 | 79 | 115 | 10 | 50 | 16.7 | 16.3 |
| 3 | 101 | 108 | 6 | 50 | 10.1 | 20.2 |
| 4 | 96 | 113 | 4 | 50 | 18.9 | 21.4 |
| 5 | 117 | 126 | 26 | 12 | 19.7 | 20.7 |
| 6 | 95 | 105 | 24 | 37 | 14.0 | 19.0 |
| 7 | 154 | 132 | 24 | 37 | 20.3 | 20.5 |
| Average | 110 | 116 | 17 | 35 | 17.4 | 19.9 |
| 4-year average | 111 | 115 | 50 | 42 | 17.4 | 19.5 |

[1] Figures in parentheses were corrected later by examination using a ladder (see text).

Table 2.--*Accuracy of rating unsuccessfully attacked trees from ground and with ladder*

| Group | Unsuccessfully attacked trees | | | | |
|---|---|---|---|---|---|
| | Ground rated | | Ladder rated | | Difference |
| | *No.* | *Percent* | *No.* | *Percent* | *Percent* |
| 1971-1 | 30 | 26 | 17 | 16 | 10 |
| 1971-2 | 71 | 39 | 41 | 23 | 16 |
| 1972-1 | 74 | 66 | 61 | 53 | 13 |
| 1972-6 | 29 | 38 | 20 | 29 | 9 |
| Total | 204 | | 140 | | |
| Average | | 42 | | 29 | 13 |

Within infested groups of rather uniform age, beetles killed larger (dominant) trees more frequently than smaller (suppressed) trees. Average diameter of killed trees was 18.6 inches; that of trees that survived attack was 15.6 inches. Larger, more dominant trees may be inherently more attractive to continued attack, leading to lethal attack densities. Smaller, suppressed trees although of equal age, may be less attractive, due to less resin exudation, resulting in sublethal attack density. For example, monoterpene vapors from resin stimulate pheromone production in several *Dendroctonus* beetles (Hughes 1973) and synergize the Douglas-fir beetle aggregating pheromone, frontalin (Furniss and Schmitz 1971). Dominant trees could still be more resistant than suppressed trees to a particular attack density, but the intense aggregation of large numbers of beetles on attractive dominant trees could result in more of them being killed than their more suppressed neighbors. We know from earlier work that the latter are attacked less densely.[3]

This tendency for beetles to kill larger trees in an unmanaged stand should not lead to the conclusion that larger trees would prove more susceptible in a managed stand. Just the opposite has been reported (Williamson and Price 1971). Shading of the stem may be an important factor. In thinned stands, more exposed stems would be less conducive to arrestment of beetles. For example, Douglas-fir beetles tend to concentrate their attacks on the shaded underside of sun-exposed windthrown trees (Furniss 1962a), probably due to their aversion of high temperatures (Vité and Rudinsky 1957).

*Population trend.*--Trend of beetle numbers during 1971 is shown in table 3. Samples with more progeny than parents (generators) made up 35 percent of the total. The remainder were static or were population sinks. Averaging the samples produced an overall population trend index of 1.1. That is, there were 10 percent more broods than parents that had attacked the samples. These broods consisted of new adults (86 percent), larvae (9 percent), and pupae (5 percent). The larvae would mature to adults in 1972, emerge, and attack weeks later than the overwintered adults. The broods would be subject to mortality from unknown factors during winter, during flight, and during invasion of new host trees. No one has accurately estimated the magnitude of such mortality in a Douglas-fir beetle generation. However, mortality does occur and we predicted (Ciesla and others 1971) that a final population index of 0.7 might prevail, arbitrarily assigning about 10 percent decrease to each of the above three categories. As it turned out, damage did diminish between 1971 and 1972 (fig. 6). Such a relationship between numbers of overwintered emerging adult beetles and numbers of trees infested subsequently has been recorded in New Mexico (Chansler 1968).

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[3] Unpublished data of senior author, presented at Second Forest Biology Workshop, Oreg. State Univ., Aug. 2, 1972.

Table 3.--*Population trend indices 1971-1974*

| Group | Samples | Trend class and frequency | | | Population trend index |
|---|---|---|---|---|---|
| | | Generators | Static | Sinks | |
| | *Number* | *Percent* | | | *Average* |
| | | | 1971 | | |
| 1 | 42 | 41 | 18 | 41 | 1.4 |
| 2 | 40 | 35 | 0 | 65 | 1.1 |
| 3 | 40 | 30 | 20 | 50 | 0.8 |
| Total | 122 | | | | |
| Average | | 35 | 13 | 52 | 1.1 |
| | | | 1972 | | |
| 1 | 20 | 30 | | 70 | 0.8 |
| 2 | 10 | 40 | | 60 | 1.0 |
| 3 | 20 | 60 | | 40 | 1.2 |
| 4 | 14 | 57 | | 43 | 1.1 |
| 5 | 20 | 30 | | 70 | 0.8 |
| 6 | 20 | 40 | | 60 | 1.3 |
| 7 | 12 | 50 | 17 | 33 | 1.0 |
| 8 | 20 | 30 | 20 | 50 | 1.0 |
| 9 | 20 | 50 | 10 | 40 | 1.4 |
| 10 | 20 | 50 | | 50 | 1.0 |
| 11 | 6 | 67 | | 33 | 1.3 |
| Total | 182 | | | | |
| Average | | 44 | 4 | 52 | 1.1 |
| | | | 1973 | | |
| 1 | 8 | 0 | 25 | 75 | 0.0 |
| 2 | 4 | 0 | 50 | 50 | 0.0 |
| 3 | 10 | 20 | 0 | 80 | 0.6 |
| 4 | 20 | 20 | 30 | 50 | 0.9 |
| 5 | 20 | 40 | 10 | 50 | 1.5 |
| 6 | 20 | 60 | 0 | 40 | 1.5 |
| 7 | 8 | 75 | 0 | 25 | 3.2 |
| 8 | 12 | 33 | 0 | 67 | 0.8 |
| 9 | 20 | 60 | 0 | 40 | 1.0 |
| 10 | 20 | 20 | 0 | 80 | 0.5 |
| 11 | 20 | 10 | 0 | 90 | 0.2 |
| 12 | 20 | 30 | 0 | 70 | 0.6 |
| 13 | 20 | 40 | 0 | 60 | 0.5 |
| 14 | 20 | 40 | 0 | 60 | 1.3 |
| 15 | 20 | 20 | 10 | 70 | 0.4 |
| Total | 242 | | | | |
| Average | | 33 | 6 | 61 | 0.8 |
| | | | 1974 | | |
| 1 | 20 | 50 | 0 | 50 | 1.2 |
| 2 | 10 | 50 | 25 | 25 | 2.0 |
| 3 | 6 | 100 | 0 | 0 | 5.0 |
| 4 | 4 | 100 | 0 | 0 | -- |
| 5 | 20 | 70 | 0 | 30 | 2.9 |
| 6 | 20 | 80 | 10 | 10 | 3.2 |
| 7 | 20 | 70 | 10 | 20 | 2.1 |
| Total | 100 | | | | |
| Average | | 70 | 6 | 24 | 2.5 |

*Natural enemies*.--Abundance of larvae of predators and parasites on bark samples is shown in table 4. The braconid, *Coeloides brunneri* Vier., was most abundant followed by dolichopodids, *Medetera* spp. Clerids (*Thanasimus undatulus* Say and *Enoclerus sphegeus* [Fab.]) and the ostomid, *Temnochila chlorodia* (Mann.), were scarce. We know that *E. sphegeus* migrates to the root crown in midsummer, before we sampled. Why *T. chlorodia* was not more abundant is puzzling. Elsewhere *T. chlorodia* was relatively more abundant in an area where an infestation had subsided about two years previously. The relative abundance of certain predators such as *T. chlorodia* could be a key factor in evaluating outbreaks of the Douglas-fir beetle, but only further investigation will tell.

Table 4.--*Densities of natural enemies on bark samples, 1971-1974*

| Group | Samples | *Coeloides brunneri* | *Medetera* spp. | Cleridae | *Temnochila chlorodia* |
|---|---|---|---|---|---|
| | *Number* | - - - - - - - - - *Number per* | *ft²* - - - - - - - - - - - - - - - - | | |
| 1971 | | | | | |
| 1 | 42 | 12.6 | 0.7 | 0.2 | 0.2 |
| 2 | 40 | 6.2 | 0.7 | | |
| 3 | 40 | 14.5 | 0.7 | 0.2 | |
| Total | 122 | | | | |
| Average | | 11.1 | 0.7 | 0.2 | 0.1 |
| 1972 | | | | | |
| 1 | 20 | 14.5 | 0.5 | | |
| 2 | 10 | 21.0 | 6.0 | | |
| 3 | 20 | 28.0 | 1.0 | 1.0 | |
| 4 | 14 | 1.4 | 1.4 | | |
| 5 | 20 | 10.5 | 0.5 | 0.5 | |
| 6 | 20 | 12.0 | | 0.5 | |
| 7 | 12 | 9.1 | 1.7 | | |
| 8 | 20 | 13.0 | 1.0 | | 0.5 |
| 9 | 20 | 3.5 | 7.5 | 2.0 | |
| 10 | 20 | 19.0 | 1.5 | 0.5 | |
| 11 | 6 | 3.3 | 3.3 | | |
| Total | 182 | | | | |
| Average | | 13.0 | 2.0 | 0.5 | 0.05 |
| 1973 | | | | | |
| 1 | 8 | -- | | | |
| 2 | 4 | 5.0 | | | |
| 3 | 10 | 4.0 | | | |
| 4 | 20 | 1.5 | | | |
| 5 | 20 | -- | | | |
| 6 | 20 | 3.5 | 1.0 | | 1.0 |
| 7 | 8 | 13.7 | 1.2 | | |
| 8 | 12 | 10.0 | 0.8 | | 0.8 |
| 9 | 20 | 7.5 | 3.5 | | 2.0 |
| 10 | 20 | 2.5 | 1.0 | | |
| 11 | 20 | 5.5 | 2.0 | | |
| 12 | 20 | 5.5 | 0.5 | | |
| 13 | 20 | 2.5 | 0.5 | | |
| 14 | 20 | 16.0 | 1.5 | | |
| 15 | 20 | 4.0 | 2.5 | | |
| Total | 242 | | | | |
| Average | | 5.2 | 1.1 | | 0.3 |
| 1974 | | | | | |
| 1 | 20 | 16.5 | 2.5 | 0.5 | |
| 2 | 10 | 5.0 | 5.0 | | |
| 3 | 6 | 6.7 | 5.0 | | |
| 4 | 4 | 7.5 | 7.5 | | |
| 5 | 20 | 8.5 | 3.0 | | |
| 6 | 20 | 11.0 | 1.5 | | |
| 7 | 20 | 10.0 | 0.5 | | |
| Total | 100 | | | | |
| Average | | 10.4 | 2.6 | 0.1 | |

## FOURTH GENERATION OF OUTBREAK (1972)

*Characteristics of attacked trees.*--The average age of attacked trees was 118 years (R = 72-186+) (table 1). Rate of successful attack increased with tree age and diameter.

Unsuccessfully attacked trees were proportionately more abundant in 1972 (59 percent) than in 1971 (31 percent). This may have been due to beetles having killed many of the more susceptible trees in 1972, and because weather was favorable to tree growth in 1972. Increased moisture is associated with increased resistance of trees to the Douglas-fir beetle (Rudinsky 1966). The host is a dominant factor in regulating Douglas-fir beetle populations; other biotic factors, such as predators, seem to be more limiting at lower population levels.

*Characteristics of groups.*--The size of groups varied considerably, ranging from 14 to 266 trees (table 1) but a general decline in group size was evident to aerial observers during 1972. Two of the larger groups (No. 1 and No. 3) resulted from attraction created by deployment of frontalin, an aggregating pheromone of the Douglas-fir beetle. We are not sure how representative they were.

The physiographic and stand characteristics related to groups are summarized in table 5. Within these groups, attacked Douglas-fir averaged 79 per acre. Elevations of sample groups ranged from 2,380 to 3,705 ft above sea level. Eight groups occurred on generally warm aspects, three groups on cooler aspects. Nearly all groups were located at midslope or higher and most were on upper slopes, due perhaps to Douglas-fir being more prevalent there and perhaps also to the beetle's flight behavior, and the rising of odors of trees and pheromones. Species of plants that indicate contrasting moisture conditions occurred in admixture and we conclude that a better measure of moisture availability is needed to seek to correlate that factor with susceptibility.

Two pairs of groups of attacked trees are compared in table 6. One member of each pair was attacked in 1971, the other in 1972. Group size ranged from ca 1 to 2 acres and average age varied from 95 to 120 years. Site indexes ranged from 77 to 83 (Brickell 1968), good for Douglas-fir growth. All were in the western redcedar-*Pachistima* habitat type, a further indication that the sites were productive. Soil was deep, with the exception of group No. 1 (1971) which had hardpan at 12 to 18 inches depth.

Infested stands ranged from 251 to 361 ft$^2$ basal area (81 to 124 percent of normal), substantiating our visual impression that they tended to be densely stocked (fig. 7). In three of the four groups we measured, Douglas-fir comprised 64 to 75 percent of the stand basal area; the fourth group was 49 percent Douglas-fir. Even the least of these percentages is relatively high for the mixed conifer stands commonly occurring in the cedar-*Pachistima* habitat type.

Results of sampling of understory trees less than 7.6 inches d.b.h. on ten 4-milacre quadrats per plot are summarized in table 7. The understory trees were 95 percent grand fir; the remainder were western redcedar. Understory trees may have added to moisture stress of Douglas-fir but will probably be more important in changing composition of the stand when released by killing of the overstory.

*Population trend.*--Trend of the beetle population during 1972 is contained in table 4. Although 52 percent of the samples were generators of brood, compared to 35 percent in 1971, the average trend index was 1.1 both years. However, the absolute population would have declined in proportion to the fewer number of successfully attacked trees in 1971 compared to 1972. As we have noted, the proportion of unsuccessfully attacked trees increased, and group size decreased during this period. The absolute population must, therefore, have decreased from 1971 to 1972.

Table 5.--*Physiographic features and moisture indices of groups of Douglas-fir beetle attacked trees, 1972-1973*

| Group | Elevation | Aspect[1] | Slope position | Moisture index[2] |
|---|---|---|---|---|
| | *Feet* | | | |
| | | 1972 | | |
| 1 | 2,700 | SSE w | Midslope | 1, 3 |
| 2 | 2,840 | NNW c | Upper slope | 1, 3 |
| 3 | 2,700 | WSW w | Bench | 1, 2, 3 |
| 4 | 3,070 | WNW w | Upper slope | 1, 2, 3 |
| 5 | 3,425 | ENE c | Upper slope | 1, 2, 3 |
| 6 | 3,290 | SSW w | Ridge | 1, 3 |
| 7 | 2,760 | SSW w | Bench | 3 |
| 8 | 2,380 | WSW w | Ravine | 1 |
| 9 | 3,700 | SSE w | Ridge | 1, 3 |
| 10 | 3,100 | NW c | Midslope | 1, 2, 3 |
| 11 | 2,920 | WSW w | Midslope | 1, 2, 3 |
| | | 1973 | | |
| 1 | 2,990 | SSW | Ridge | 1, 2, 3 |
| 2 | 3,005 | S | Slope | 3 |
| 3 | 1,710 | SSE | Slope | 1, 2 |
| 4 | 1,940 | NW | Ridge | 1, 2, 3 |
| 5 | 1,930 | SSW | Slope | 1, 2, 3 |
| 6 | 1,905 | SSE | Slope | 1, 2 |
| 7 | 1,710 | NNW | Slope | 1, 2, 3 |
| 8 | 1,730 | NNW | Slope | 1, 2, 3 |
| 9 | 1,650 | ENE | Slope | 1, 2, 3 |
| 10 | 1,700 | W | Slope | 1, 2, 3 |
| 11 | 3,650 | SSE | Ridge | 2, 3 |
| 12 | 3,380 | SSW | Slope | 1, 3 |
| 13 | 3,380 | SSE | Slope | 1, 3 |
| 14 | 3,670 | SSE | Ridge | 1, 2, 3 |
| 15 | 2,700 | W | Slope | 1, 2, 3 |
| | | 1974 | | |
| 1 | 3,675 | N | Ridge | 1, 2, 3 |
| 2 | 2,820 | SSW | Slope | 1, 2, 3 |
| 3 | 2,900 | WSW | Slope | 1, 2, 3 |
| 4 | 3,040 | SSW | Ridge | 1, 2, 3 |
| 5 | 2,950 | NNW | Slope | 1, 2, 3 |
| 6 | 3,100 | WSW | Slope | 1, 2, 3 |
| 7 | 3,500 | NW | Slope | 1, 3 |

[1] w = warm, c = cool aspect.

[2] Vegetation present: 1 = grass, snowberry (dry); 2 = ninebark, oceanspray (intermediate); 3 = grand fir (moist).

Table 6.--*Initial and residual stand density of groups killed by Douglas-fir beetle in 1971 and 1972*

| Group | | Stand age | Site index | Area | Trees per acre: Total | Trees per acre: DF | Trees per acre: % DF | Basal area per acre: Total | Basal area per acre: DF | Basal area per acre: % DF | Percent normal |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Year* | *No.* | | | *Acre* | *No./acre* | *No./acre* | | *Ft²/acre* | *Ft²/acre* | | |
| | | | | | Initial Stand[1] | | | | | | |
| 1971 | 1 | 106 | 82 | 1.26 | 240 | 152 | 63 | 278 | 202 | 73 | 96 |
| 1972 | 1 | 120 | 83 | 1.92 | 155 | 94 | 60 | 251 | 160 | 64 | 81 |
| 1971 | 2 | 95 | 80 | 2.16 | 220 | 143 | 65 | 340 | 233 | 68 | 124 |
| 1972 | 6 | 116 | 77 | 1.64 | 213 | 71 | 33 | 361 | 175 | 49 | 118 |
| | | | | | Residual Stand[2] | | | | | | |
| 1971 | 1 | 106 | 82 | 1.26 | 149 | 62 | 41 | 133 | 57 | 43 | 46 |
| 1972 | 1 | 120 | 83 | 1.92 | 88 | 27 | 31 | 126 | 35 | 28 | 41 |
| 1971 | 2 | 95 | 80 | 2.16 | 133 | 56 | 42 | 159 | 52 | 33 | 58 |
| 1972 | 6 | 116 | 77 | 1.64 | 162 | 20 | 12 | 216 | 31 | 14 | 71 |

All groups are in cedar-*Pachistima* habitat type.

[1] Total stand includes the Douglas-fir trees infested with beetles.

[2] Residual stand remaining after infested Douglas-fir trees were subtracted.

Of the brood on the bark samples, 21 percent were immature (larvae 17 percent; upae 4 percent), compared to 14 percent (larvae 9 percent; pupae 5 percent) in 1971. shift toward immature overwintering brood has important implications. Instances have een recorded (Furniss 1965, McMullen 1970) in which infestations subsided when all rood eventually overwintered as larvae and stayed in the trees for 2 years. This was ccompanied by high mortality of brood; but, exceptionally cold weather persisted prior those events.

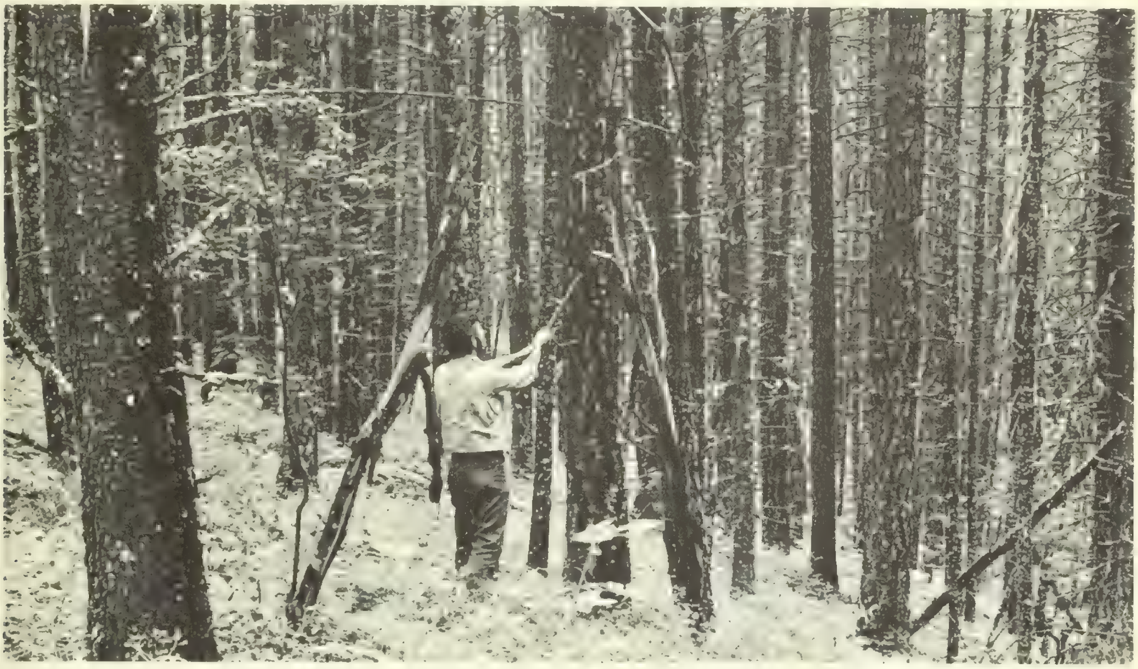

Figure 7.--A young stand attacked by Douglas-fir beetles. Overstocking and high proportion of Douglas-fir are factors involved when young stands are attacked.

Table 7.--*Stocking of understory trees in four groups attacked by Douglas-fir beetles in 1971 and 1972*

| | Plot | | | |
|---|---|---|---|---|
| | 1971-1 | 1971-2 | 1972-1 | 1972-6 |
| Stocked quadrats (percent) | 40 | 70 | 100 | 80 |
| Trees (Σ No./acre) | 200 | 450 | 1,200 | 875 |

Progressive increase in the proportion of immature brood overwintering may benefit species. Weather and host conditions may alternately favor either early- or late-erging brood (Atkins and McMullen 1958) due to seasonal change in precipitation and mperature. Such a possibility and lack of control over it makes prediction difficult. ditional documented case histories, such as ours, should assist in determining the obabilities involved.

*Natural enemies.*--Abundance of natural enemies of Douglas-fir beetles on bark mples during 1972 is shown in table 4. Their relative abundance was the same as ring 1971. However, except for *C. brunneri*, they were less numerous per square foot 1972, although a decline in number of trees killed should have resulted in their ing more abundant per unit area of bark even if their populations remained static.

*Root rot association.*--All three trees that we examined in the first group for ro diseases had been attacked by Douglas-fir beetles in the previous year. They had been rated as resistant, semiresistant and susceptible, based on success of beetle attack. Their roots contained galls below ground, which apparently developed after a fire more than 50 years ago. The galls varied in size and in extent of roots infected. In location and form, galls were similar to *Agrobacterium tumefaciens* (E.F. Sm. and Town. Conn, but presence of other organisms precluded isolating the specific cause.

We also found *Armillaria mellea* (Vahl ex Fr.) Quél. associated with diseased root of the three trees. In one root we found a spindle-shaped canker 100 cm x 8.5 cm with blue-black streaks beneath. In laboratory cultures, this canker yielded *Verticicladie wagenerii* Kendr., the cause of "root-stain disease" (Leaphart 1960). This fungus was not known previously to infect Douglas-fir.

Two of the three trees that we selected from the second group had been attacked b beetles; one successfully and one unsuccessfully; the third tree had not been infested We found extensive *A. mellea* in both beetle-attacked trees and *A. mellea* together with *Poria subacida* (Fr.) Sacc. and streaks suggesting root-stain disease in the unsuccessfully attacked tree. Cultures confirmed that *V. wagenerii* was associated with the streaks. All roots of the unattacked tree were healthy although it was surrounded by infested and infected trees.

The amount of root disease was generally correlated with success of beetle attack Three trees with roots 70 to 90 percent destroyed were successfully invaded by beetles Two with 30 to 40 percent root destruction had mostly unsuccessful attacks and one wit no diseased roots had no attacks.

## FIFTH GENERATION OF OUTBREAK (1973)

*Characteristics of attacked trees.*--Average age of attacked trees was 117 years (R = 80-183) (table 1).

*Characteristics of groups.*--Group size declined from an average of 79 to 22 trees between 1972 and 1973 (table 1) in spite of a record drought that summer. Proportion unsuccessfully attacked trees also diminished, no doubt as a result of moisture stress (Rudinsky 1966).

Sample groups occurred between 1,650 ft and 3,670 ft elevation, mainly on warm slopes (table 5). Moisture indicating plants were again too diverse to be of utility characterizing sites.

*Population trend.*--Trend of beetle population declined to a ratio of 0.8 brood pe parent (table 3) and less than 1 percent of the overwintering brood was immature compa to 21 percent in 1972 and 14 percent in 1971. The faster rate of maturation was doubtless due to the warmer weather in 1973, a year of record drought.

*Natural enemies.*--*C. brunneri* continued most abundant among natural enemies followed by *Medetera* spp. (table 4). However, density of most natural enemies declined from the previous year, perhaps influenced by the decline in average productivity of Douglas-fir broods (table 3).

## SIXTH GENERATION OF OUTBREAK (1974)

*Characteristics of attacked trees and groups.*--Average age of attacked trees was 110 years (R = 79-154) (table 1). Thirty-seven percent of the attacked trees were rat unsuccessful, up 8 percent over 1973.

Average number of attacked trees per group was 17, lowest of the 4 years. Infested groups occurred on ridges and drier slopes, from 2,790 to 3,650 ft above sea level (table 5). Groups occurred predominantly on warm aspects, but not necessarily at frequency different from green Douglas-fir, which predominates on warm aspects.

*Population trend.*--Population trend index (2.5) increased threefold over 1973 (table 3). Reasons for the increased population may be due to the 1973 drought which resulted in high moisture stress in trees, effects of which may have persisted in 1974 (Rudinsky 1966). Also involved in the higher population may have been a lower attack density (6.9/ft$^2$) in 1974 compared to 9.5/ft$^2$ in 1973, which would have resulted in less intraspecific competition and consequent greater brood survival (Schmitz and Rudinsky 1968; McMullen and Atkins 1961). The high population index resulted in a threefold increase in damage in the Clearwater River drainage when the broods emerged in 1975 (Livingston and others 1977).

*Natural enemies.*--The larval parasite, *Coeloides brunneri*, continued to be the most prevalent natural enemy followed by *Medetera* spp. (table 4). The ostomid, *Temnochila chlorodia*, was absent from samples and only one larva of the clerid, *E. sphegeus* was tallied.

# CONCLUSIONS

We note the following, based on our observations of the infestation: (1) Attacked groups were on good sites typical of the Clearwater drainages--in stands composed mainly of Douglas-fir, and that were denser than normal. (2) Age of attacked groups varied; but some averaged only ca 90 years old, unusually young in relation to other Rocky Mountain infestations. (3) Rate of tree-killing declined in the fourth beetle generation (1972). (4) The decline in the infestation was accompanied by cessation of major stand disturbances, smaller groups of infested trees, higher proportion of unsuccessfully attacked trees, and an average beetle population index of 1.1 in early fall. (5) Little change was apparent in density of immature parasites and predators on bark samples between years, and several were scarce on samples throughout our study. (6) Tree susceptibility to beetle attack may be related to infection by root rots.

Additional outbreaks should be studied similarly, for a longer period, especially at their inception, but factors that seem related to the onset or decline of an outbreak are: disturbances, stand density, success of attack (host resistance), population index, root rot, and, possibly, habitat type. All warrant further study.

We offer the following verbal model to describe the functioning of factors that regulate Douglas-fir beetle abundance and damage in the Northern Rocky Mountains:

> Disturbances such as windstorms and fire contribute to increased Douglas-fir beetle populations. When such disturbances cease, beetles seek out and attack live trees; their success depends upon the susceptibility of the attacked trees. Trees damaged by snow-breakage, possibly those defoliated by tussock moths, stressed by drought, or infected with root rots are susceptible and contribute to furtherance of the outbreak.
>
> The proportion of Douglas-fir in a stand, and its density and age are positively correlated with susceptibility. Any of these factors can limit damage, but high density can result in somewhat younger trees being attacked.

> As the susceptible trees are killed by beetles or removed by logging, or, as the environmental conditions improve (favoring growth and water relations), resistance to population expansion mounts. Size of infested groups declines and a higher proportion of attacked trees survive. Numbers of natural enemies appear to be independent of prey density; influence of enemies increases after the bark beetle population subsides. Populations are maintained at an endemic level primarily by tree resistance and natural enemies.

We recommend that managers seek to prevent outbreaks by: (1) thinning young stan and maintaining desirable spacing until harvest, and (2) removing susceptible trees s as those that are windthrown, snow-broken, or infected with root rot. Such preventiv action is the most effective and economical method for combatting beetle damage.

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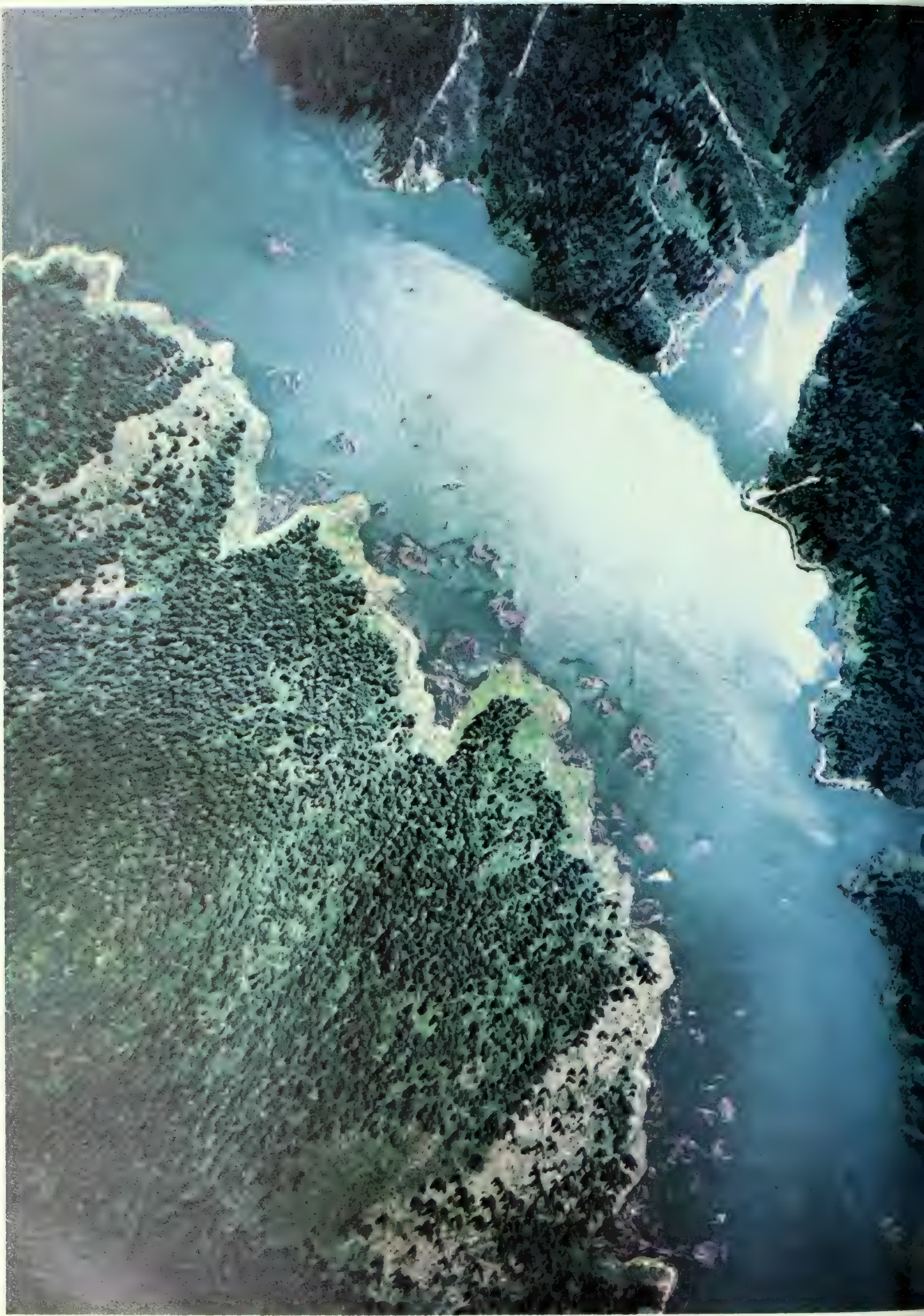
BACK COVER:
Vertical view of Dworshak Reservoir with log debris from clearing. Douglas-fir beetle killed trees are visible in lower left.



# INCLUDING THE FISHERY SYSTEM IN LAND PLANNING

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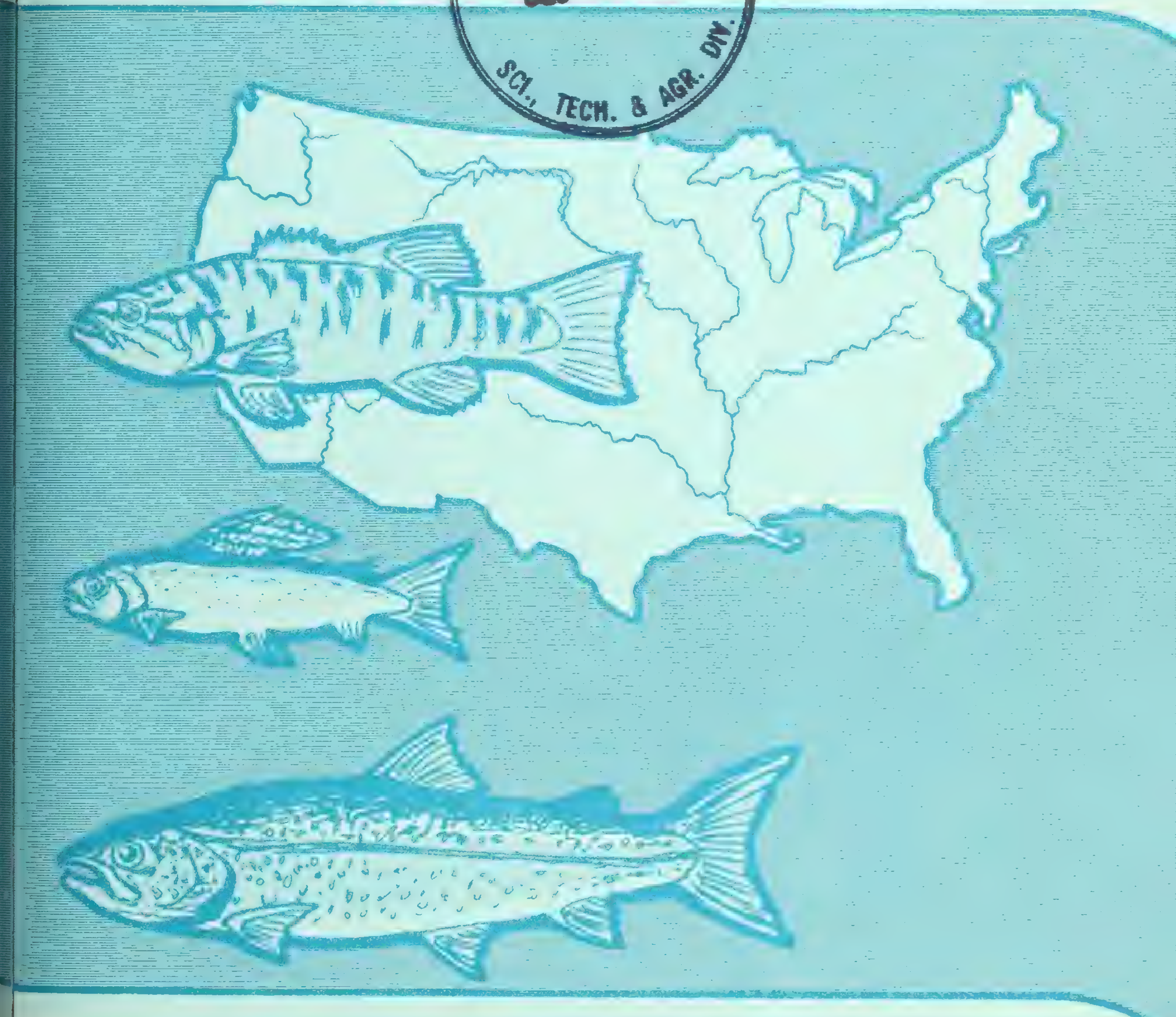

DA Forest Service General Technical Report INT-60
rmountain Forest and Range Experiment Station
est Service, U.S. Department of Agriculture

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# INCLUDING THE FISHERY SYSTEM IN LAND PLANNING

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# RESEARCH SUMMARY

The USDA Forest Service uses a geomorphic analysis that classifies units of land in its Land Systems Inventory. This inventory provides managers with a description of the geology, geomorphic processes, and watershed conditions within any given area of land. Similar areas of land can then be identified, classified, and mapped. The inventory information is then used to determine the type and intensity of land uses each of these stratified land areas can provide and still protect the environment and allows land managers to intelligently plan for future land uses. Although the system provides some protection for the aquatic environment, the inventory, built on terrestrial descriptions, does not provide the information needed for managing aquatic resources.

Through the study reported here, a system was developed to integrate all streams and their fisheries into the Land Systems Inventory at the landtype association level and to include most streams and their fisheries at the landtype level of planning. This integration was possible because not only do similar lands have similar vegetation and geology but because similar lands in the natural state also have similar streams and fisheries.

Similar lands have similar fisheries because watersheds influence the development of the abiotic and biotic components of the stream. The abiotic components of the stream dictated fish biomass and species composition. Therefore, fish biomass and species composition can be determined at levels of accuracy needed in land use planning by using the Land Systems Inventory that identifies similar lands. Thus for the first time the landmanager has a planning system covering large areas that includes both the terrestrial and aquatic environments in the final allocation of resources.

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# INTRODUCTION

Because they work with aquatic ecosystems on an element-by-element basis, fishery iologists have a difficult time working fishery information into the interdisciplinary rocesses used in land-use planning (Platts 1976a). This piecemeal approach makes it ifficult to present fishery information in a form to meet the requirments of the National nvironmental Policy Act of 1969, the Resource Planning Act of 1974, and the National orest Management Act of 1976.

Fishery information is difficult to integrate into the planning process because nventory methods are too crude to adequately document the fishery (Platts 1976b). lso, biologists do not have a procedure that will unite the fishery information with he terrestrial land system classifications managers rely on for land use planning Arnold 1975). This report presents a method that can be used to integrate the fishery nto a land classification system in selected mountainous lands in Idaho.

To assign streams for resource use managers need information similar to that reuired to allocate lands as provided in the Forest Services' Land Systems Inventory. anagers must know the inherent capability of streams, the resources the streams prouce, and the influences on these stream resources from surrounding land management rograms. The Land System Inventory provides biologists with a blueprint that will rovide this basic information over broad land areas. This inventory will also allow he information to be used at levels of planning needed to fit the land units used in he planning. Biologists need a nationally accepted planning process that will include he fishery in land use planning. This report demonstrates a method that may work over road areas of mountainous lands. The report is based on a study that successfully interated the fishery into a Land Systems Inventory that covered 397 square miles (1,028 m$^2$) of lands in the South Fork Salmon River, Idaho.

# TTEMPTS TO WORK THE FISHERY INTO LAND PLANNING

## The ECOCLASS System

Individuals and teams have attempted for many years to develop ecosystem classification models that would include the aquatic system. Corliss and others (1973)[1] esigned ECOCLASS in an attempt to build a single classification system that would nify all systems (terrestrial and aquatic) that would fulfill the needs of both esearch and management planning. ECOCLASS was designed to be used at all required evels of planning, with the lowest level being the on site or project level. The ajor failure in ECOCLASS was that the aquatic environment could not be united with he terrestrial environment at levels needed for planning.

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[1] Corliss, J. C., Robert D. Pfister, William S. Platts, and others. 1973. ECOCLASS method for classifying ecosystems - a task force analysis. USDA For. Serv., Intermt. or. and Range Exp. Stn., Missoula, Mont., 52 p.

## Land Systems Inventory

Wertz and Arnold (1972) developed a Land Systems Inventory for the Forest Service that delineates similar mapable land units of the sizes required for planning that could also be used to map similar aquatic units. Their system, capable of covering large areas, demonstrates the benefits of an inventory that has application to land-use planning, decisionmaking, and management because it can fit the different levels of planning from the project level to national level.

Wertz and Arnold's land base units represent many levels (narrow to broad) of environmental descriptions essential for separating the planning unit into successivel smaller land components. Within this concept, broad land units can be subdivided into smaller, more homogeneous units; likewise smaller land units in the system can be combined to form broad land units to meet planning objectives.

Wertz and Arnold (1972) provided the first workable model that could unite the condition and capability of the aquatic environment with the condition and capability of the terrestrial environment within the same unit of land.

Soil scientists in the USDA Forest Service, Northern Region, have been classifyin and mapping national Forest lands at the landtype level using an almost identical Land Systems Inventory used in the Intermountain Region. Landtypes are visually identifiab units of land resulting from homogeneous geomorphic and climatic processes and range from 1/10 to 1 square mile (2.59 $km^2$). The Land Systems Inventory was also devised to provide information to meet specific land use planning objectives for the different resource uses (USDA 1976). The Northern Region system of classification incorporates the sciences of geomorphology, geology, soil science, hydrology, and plant ecology, but did not incorporate the fishery. This system did provide information that would assist in determining some environmental conditions that could influence the fishery: (1) average annual precipitation, (2) snow pack conditions, (3) average annual air temperature, (4) stream flow timing, (5) water yield, and (6) sediment pollution hazar

Wendt, Thompson, and Larson (1975), expanding the work of Wertz and Arnold (1972) developed procedures for use in the Forest Service that would provide mapable land base information useful to all disciplines. This method starts at the physiographic province level and steps down through selected levels to the landtype level. Their goal was the same as Wertz and Arnold's (1972) -- to systematically define the land units within any area in terms of the information required by the planning level.

Because their system focuses on a common land unit, the inventories are easily assembled and readily understood among interdisciplinary scientists. By uniting the stream systems with this land system inventory, information available from other scientists concerning geomorphology, climate, soils, and vegetation can be directly related to the fishery.

## Valley Systems Inventory

Cole (1972), in an inventory procedure for stream hydrology, extended the Forest Service Land Systems Inventory down to the valley level of classification. The valley type is a refinement of those landtypes containing valleys that did not originally all an adequate description of the valley bottoms. By classifying the valley in a form useful for planning, Cole (1972) gave the fishery biologist a planning system that is only three levels above that needed for intensive fishery planning. Below the valley classification only the habitat type and site levels of information are necessary to fulfill all requirements of planning and management.

Cole's (1972) valley types by themselves would not be adequate for all planning, as the pollution received by a stream often comes from hill slopes as well as the valley bottom. Collotzi (1976) related certain stream physical conditions to valley type but did not include the fishery as it would react to these conditions. Collotzi's (1976) and Cole's (1972) approaches will enhance the Land Systems Inventory when the fishery information can be worked into this level with confidence.

## Aquatic-Geomorphic System

Platts (1974) worked the fishery information into the Land Systems Inventory at two of the middle levels of land classification. This study sparked interest among land managers (Pence 1976) and may have initated fishery biologists (Collotzi 1976, Espinosa 1978) to attempt working the fishery into other levels of planning. The approach by Platts (1974) is seldom used because the system demands a reliable data base and the system was worked into the Land System Inventory at only the two levels. Thus the land managers could not use this system at levels they needed for intensive management. This system does have merit in that it moves away from the subjective methods of developing input for land use planning towards a more reliable quantitative approach.

## Wetlands Classification

The USDI Bureau of Sport Fisheries and Wildlife (1976) in "Interim Classification of Wetlands and Aquatic Habitats of the United States," presented a method for classifying wetlands and aquatic habitats. This system dealt strictly with aquatic habitats and, at this time, does not allow the fishery to be worked directly into land use planning of surrounding lands or resources. Therefore, without further development this system will not fit into the broad interdisciplinary planning effort.

Bailey's (1976) Regionalization Classification system was used by the Fish & Wildlife Service (1976) for stratifying Wetlands Classification. If the Wetlands Classification is worked into Bailey's (1976) system as Bailey's system is stepped down to describe smaller size land units, (down to at least the landtype level) then the Wetlands system could be worked into land use planning once the fishery was also determined at this level.

## Regionalization Classification

Bailey (1976) has recently classified and mapped the United States at the regional level. Terrestrial abiotic and biotic components are classified simultaneously, therefore the system is built on their interrelations and interactions. Because aquatic life is dependent on both the abiotic and biotic parts of the terrestrial environment, as Bailey's (1976) system is stepped down to classify smaller areas of land via the Land Systems methodology, biologists should find it will fit fishery needs.

## The ECOSYM System

ECOSYM is being developed and field tested under The U.S. Forest Service SEAM (Surface Environment and Mining) Program by Utah State University (Davis and Henderson 1976). ECOSYM is different from the mapable land unit classification approach develope by Wertz and Arnold (1972), Platts (1974), and Wendt, Thompson and Larson (1975). ECOSYM authors contend that while the classification approach has provided a tool for supplying specific information at particular locations, the information supplied has not been useful or applicable to other locations.

ECOSYM was designed not only to serve as a system for classifying local lands, but also to serve as a general system that will allow information gathered in one area to be used in other areas. The authors of ECOSYM believe that land classification schemes such as Daubenmire's (1968) and ECOCLASS (Corliss and others 1973) are based heavily on subjective criteria and are not applicable to a wide range of management questions.

ECOSYM differs from ECOCLASS in that ECOSYM builds a broadly based information system using separate ecosystem classifications. This framework attempts to include all important ecosystem components to answer specific questions. ECOSYM has yet to be validated, while the Land Systems 5 model has been tested with good results.

The techniques used in this study to work the fishery into a planning system should accomodate either ECOSYM or the Land System Inventory. At present the method is directed toward the Land Systems model, the principal model being used to collect inventory data for land use planning on National Forest lands (Wendt, Thompson, and Larson 1975).

# LAND CLASSIFICATION STUDY

## Study Objectives

By quantifying components of the stream environment, fish populations and fish community structure within designated land units, the following hypothesis could be tested: similar land units with similar lithology contain similar stream environments and similar fisheries. If this null hypothesis is not rejected, then land classification systems could be utilized to describe and classify streams and fisheries and this information could be worked into the land-use planning process using the land units common to other disciplines.

The objective of this study then was to test the following two phases of the hypothesis: (1) the stream and its fisheries can be worked into the Land Systems Inventory at selected levels of classification; and (2) stream environments and their fisheries can be determined from the land systems classification at the landtype association and landtype levels once the sub-sampling of the stream environment and its fisheries is sufficient.

## Study Area

The study area is in the southern portion of the Northern Rocky Mountain physiographic province and is located entirely within the Idaho Batholith (fig. 1). About 397 square miles (1,028 km$^2$) of the upper 52 miles (84 km) of the South Fork Salmon River (SFSR) drainage in west-central Idaho were included in the analysis. Data were collected from 38 tributary streams by studying 2,482 transects to document streams and streamside environments, and by sampling 291 fish study plots for estimates of fish standing crop and fish community structure.

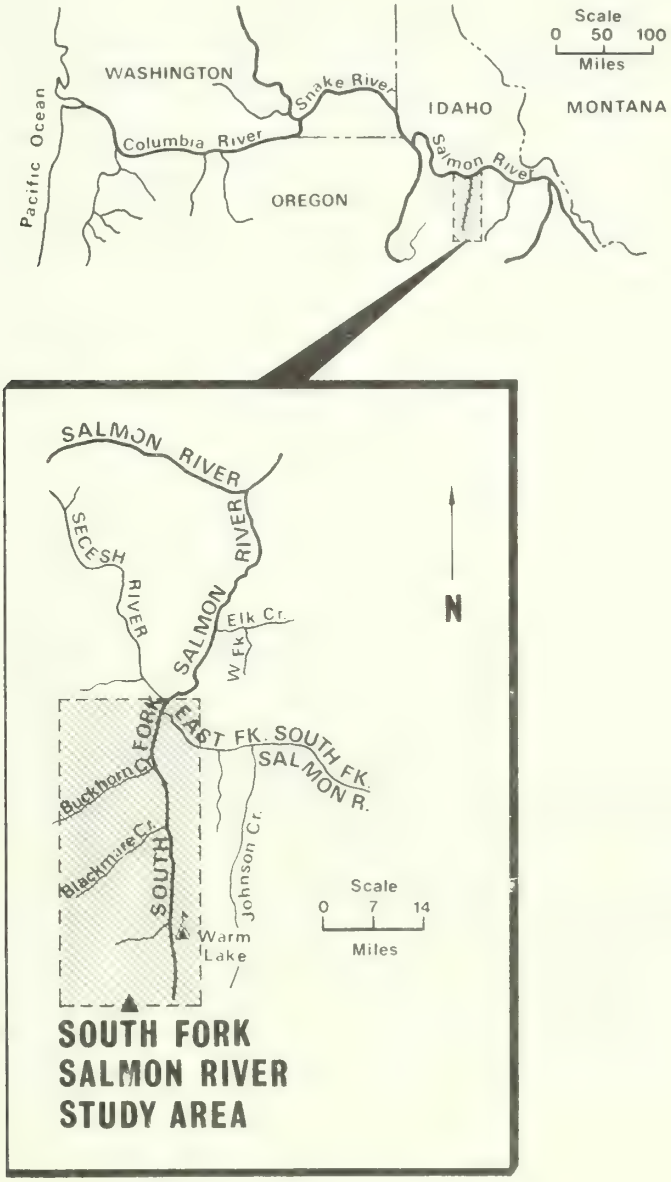


Figure 1.--Location of the study area and its relationship to the Columbia River drainage.

The study area contains a large array of landtypes resulting from land-forming processes occurring since the rise of the batholith. The main land-shaping forces have been streams, glaciers, and mass-wasting processes causing high geologic erosion, especially at the higher elevations. Faulting, folding, and uplift have also played an important but less extensive role in the land-forming processes.

## FISHERY

The study area has historically contained the largest salmon run in Idaho composed entirely of summer chinook salmon {*Oncorhynchus tshawytscha* (Walbaum)}. Because of passage problems in lower Snake and Columbia River dams, this run is now only of remnan size. Steelhead trout (*Salmo gairdneri* Richardson), fluvial cutthroat trout (*Salmo clarkii* Richardson), rainbow trout (*Salmo gairdneri* Richardson), Dolly Varden {*Salvelin malma* (Walbaum)}, brook trout {*Salvelinus fontinalis* (Mitchill)}, mountain whitefish {*Prosopium williamsoni* (Girard)}, sculpin (*Cottus* spp.), dace (*Rhinichthys* spp.), lamprey {*Entosphenus tridentatus* (Gairdner)}, and mountain sucker {*Catistomus platyrhynchus* (Cope)} also occupy the study streams. The study streams often have channel gradients that are too steep for high production of salmonoids, although salmonoids have adapted to almost all streams in the study area.

The study streams seldom receive fishing pressure because of poor access and better fishing in surrounding areas. Thus, fish mortality is due almost entirely to natural causes, and standing crops provide a measure of fish populations under natural conditions. Standing crops of fish yield unbiased estimators of the quality and size of stream environments.

## STUDY STREAMS

The average elevation of study streams is 5,653 feet (1,719 m) and stream elevatio range from 4,370 to 7,407 feet (1,328 to 2,252 m). The streams occur within 12 differen landtypes.

The study streams offer a wide variety of aquatic habitat types representative of mountain streams in the batholith. They study streams are in natural or near-natural condition and water chemistry is uniform (Platts 1974) because the bedrock is almost entirely granitic.

The study area has been landtyped by soil scientists and hydrologists (Arnold and Lundeen 1968) and was one of the first land areas to be typed according to geomorphic processes that formed the lands.

# STREAM, FISHERY, AND LAND CLASSIFICATION

## Streams

The stream survey was conducted from 1970 through 1972 using methods outlined by Platts (1974) modified from Herrington and Dunham (1967) to increase the accuracy of the environmental descriptions and to add additional descriptors. The methods satisfactorily quantified most aquatic variables because measurements were conducted during clear, low-flow conditions.

The environmental condition of the 38 major tributaries within the study area, totaling 135 stream miles (217 km), was documented by using an average of one transect for every 93 yards (85 m) of stream. Stations were located randomly along study streams from mouth to headwaters until ephemeral stream conditions were encountered. Each station included a cluster of 5 evenly spaced transects with 50-foot (15.3 m) intervals.

A transect (channel cross section) was defined as a line running perpendicular to the centerline of the stream. The following measurements and conditional factors were recorded at each transect:

1. Stream depth at four equal intervals across the transect.
2. Channel substrate particle size classifications.
3. Stream, pool, and riffle widths.
4. Pool rating.
5. Cover, condition, and habitat type of streambanks.
6. Channel elevation and gradient.
7. Fish species and abundance.
8. Landtype association and landtype.

A given transect crossing the stream channel was divided into 1-foot (0.3 m) intervals, and the dominant streambed surface material was classified on each 1-foot section as follows:

| *Particle diameter* | *Classification* |
|---|---|
| 12 inches or over (304.8 mm or over) | Boulder |
| 3 to 11.99 inches (76.1 to 304.7 mm) | Rubble |
| 0.185 to 2.99 inches (4.7 to 76.0 mm) | Gravel |
| 0.184 inch and less (Less than 4.7 mm) | Fine sediment |

Stream areas were identified as either pool or riffle. The pools were then classified as to suitability for fish as follows:

| *Description* | *Rating* |
|---|---|
| Maximum pool diameter exceeds average stream width. Pool is over 3 feet in depth or over 2 feet in depth, with abundant fish cover. | 5 |
| Maximum pool diameter exceeds average stream width. Pool is less than 2 feet in depth or if between 2 and 3 feet in depth lacks fish cover. | 4 |
| Maximum pool diameter is less than average stream width. Pool is over 2 feet in depth, with intermediate to abundant cover. | 3 |
| Maximum pool diameter is less than average stream width. Pool is less than 2 feet in depth, with intermediate to abundant cover. | 2 |
| Maximum pool diameter is less than average stream width. Pool is less than 2 feet in depth, with no cover. | 1 |

The condition and type of each streambank were rated using the total streamside area between each transect in accordance with the following tabulation:

| *Vegetation* | | *Stability* | | *Habitat type (example)* | |
|---|---|---|---|---|---|
| Forest | 2.0 | Excellent | 2.0 | Sod, root, log | 2.0 |
| Brush | 1.5 | Good | 1.5 | Brush, rubble | 1.5 |
| Grass | 1.0 | Fair | 1.0 | Grass, gravel | 1.0 |
| Exposed | .5 | Poor | .5 | Fines, road fill | .5 |

Station and transect elevations were read with an altimeter to ±40 feet (12 m).

Channel gradients were recorded at each cluster of transects with a clinometer and equalled the average gradient over the entire 200-foot (61-m) study section.

Stream width values refer to surface water widths measured perpendicular to the flow of the stream. Average transect depths were obtained from four equidistant measurements.

## Fish Population

A total of 2.75 miles (4.42 km) of stream were sampled at 291 stations, using 4 miles (6.4 km) of prima cord. A 0.13- or 0.23-inch (0.32 or 0.57 cm) mesh net was stretched across the stream to block fish from moving out of the sampling area prior to the explosion. The net and the effectiveness of prima cord assured an unbiased collection of nearly 100 percent of the fish population within each sample area. All collected fish were identified and measured for total length.

## Land Classification

The study area was morphogenetically categorized by soil scientists according to dominant geomorphic processes into four landtype associations. These associations were further subdivided into 20 landtypes. The landtype is the lowest level of classification used in this study. Maps with overlays were used to determine the land system unit in which the selected stream or stream area occurred.

The two geomorphic levels of stratification evaluated in this study are part of a system proposed by Wertz and Arnold (1972) that contains the following categorical levels in descending order of hierarchy.

1. Site
2. Landtype phase
3. LANDTYPE
4. LANDTYPE ASSOCIATIONS
5. Subsection
6. Section
7. Physiographic province

# RESULTS

This study unified the aquatic system into two levels of the Land Systems Inventory by describing and evaluating the following *basic* aquatic environments components:

Stream channel substrate conditions
Stream channel morphology
Stream channel cover
Water column morphology
Water column movement
Streamside morphology
Streamside cover

The study also correlated the interrelationships of the basic components to the following *manifest* components:

Fish standing crops
Fish community structure
Fish diversity
Fish spatial occurrence

The basic components were then tested to see if similar landtypes within the landtype association had similar components and to determine if different landtype associations had different components. Because there was parallel similarity, this allowed the fishery to be integrated directly into the Land Systems Inventory.

The final results of the integration of the aquatic environment and its fisheries into the Land Systems Inventory appears in appendixes A and B. This unification is the most important part of this study and the detailed description of integration appears in the appendixes only because of its length. The summary analysis that follows explains why the integration was successful and shows how each of the basic and manifest elements relates to the geomorphic classifications used in the Land Systems Inventory.

### Stream Environments Within Landtype Associations

The study area was categorized into four landtype associations at the geomorphic process level--glaciated, cryic, fluvial, and depositional. Each association was sufficiently different in aquatic environment to permit separate aquatic stratification. The aquatic types, however, in the depositional land type association could be better stratified by categorizing their association into two subgroups based on whether ice or water had deposited the soils within the association.

## ANALYSIS BY BASIC COMPONENT

### Stream Channel Gradients

Stream channel gradients in the glaciated lands (table 1) greatly exceeded those of channels in the other landtype associations (fig. 2 and 3). Because mountain slope lands (fluvial landtype association), cryic lands, and valley train lands (depositional landtype association) all have moderately steep channel topography, stream channel gradients in these associations are about the same (fig. 4, 5, 6, 7, 8,).

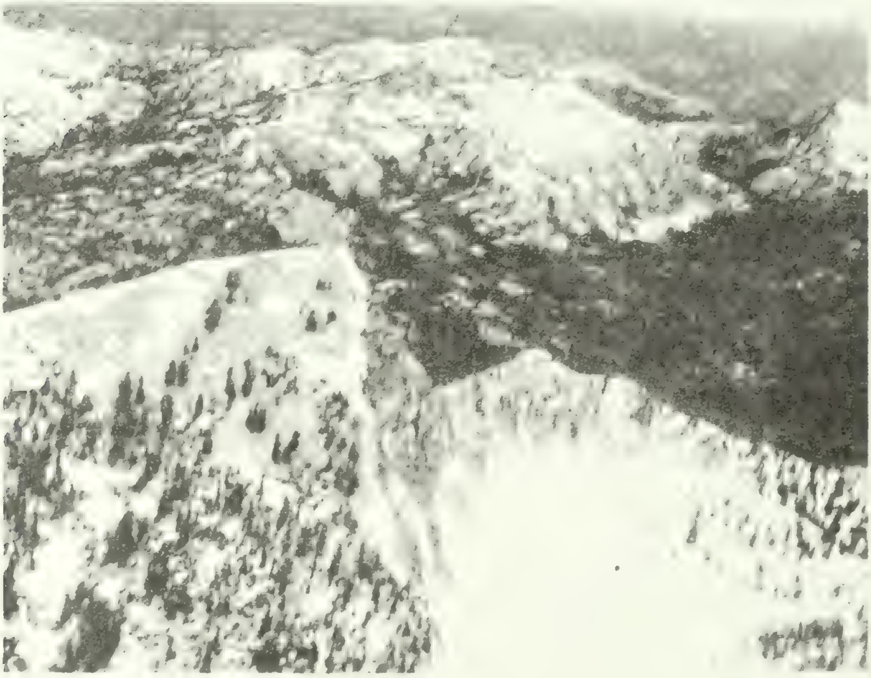


Figure 2.--Glaciated lands (foreground) which include a cirque basin landtype. The granitic bedrock is hard, unweathered, nonspalling, and slightly to moderately fractured. The depressional nature of the landscape allows for deep percolation and conversion of precipitation to subsurface flow, which regulates streamflow.

Table 1.--*Stream conditions by landtype association (95 percent confidence interval in parentheses)*

| Variable | Landtype association | | | |
|---|---|---|---|---|
| | Glaciated | Cryic | Fluvial | Depositional |
| Gradient (percent) | 10.6 (0.7) | 6.6 (2.4) | 6.3 (0.2) | 6.6 (0.3) |
| Width (feet) | 9 (1.0) | 9 (2.4) | 15 (.5) | 14 (.4) |
| Depth (inch) | 6 (.7) | 8 (2.2) | 8 (.2) | 8 (.1) |
| Riffle (percent) | 44 (4.9) | 44 (11.9) | 60 (.6) | 50 (.4) |
| Pool (percent) | 56 (6.3) | 56 (15.1) | 40 (.4) | 50 (.3) |
| Pool rating (units) | 4.1 | 3.4 | 3.9 | 3.7 |
| Channel composition (percent) | | | | |
| Boulder | 42 (4.8) | 14 (3.8) | 35 (2.1) | 32 (1.8) |
| Rubble | 16 (1.8) | 26 (7.0) | 30 (1.5) | 25 (1.4) |
| Gravel | 31 (3.5) | 20 (5.4) | 15 (1.3) | 21 (1.4) |
| Fine sediment | 11 (1.2) | 40 (10.8) | 20 (1.4) | 22 (1.5) |
| Bank environment (units) | | | | |
| Cover | 1.7 (.2) | 2.0 (.5) | 1.8 (.02) | 1.7 (.1) |
| Condition | 1.8 (.2) | 1.6 (.4) | 1.6 (.04) | 1.7 (.1) |
| Type | 1.8 (.2) | 2.0 (.5) | 1.9 (.02) | 1.9 (.02) |
| Channel elevation (feet) | 6569 | 6151 | 4971 | 5626 |
| Sample size | 300 | 55 | 858 | 1218 |

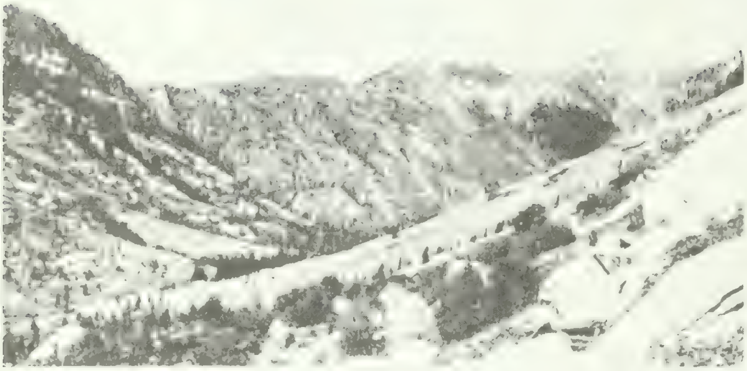


Figure 3.--Strongly glaciated landtype, with rocky ridge landtype in the background. Note the U-shape of the hanging valley in the foreground, which disappears into a larger U-shaped glaciated valley.

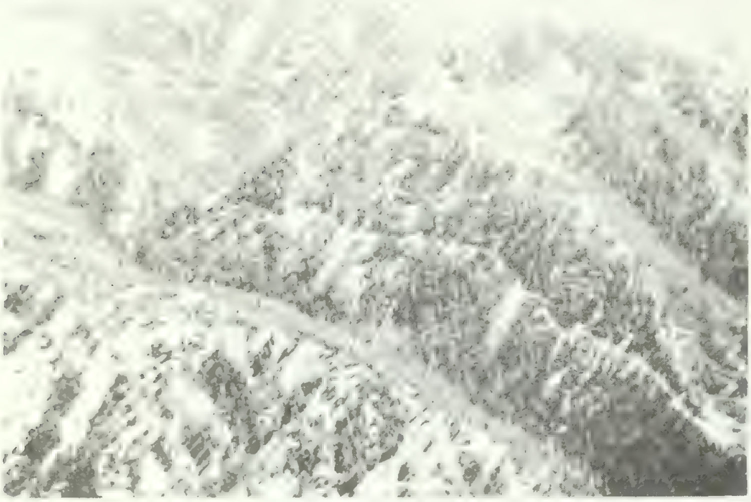


Figure 4.--Strongly dissected mountain slope landtype, with slopes between 55 to 70 percent and drainage ways spaced less than 500 feet apart.

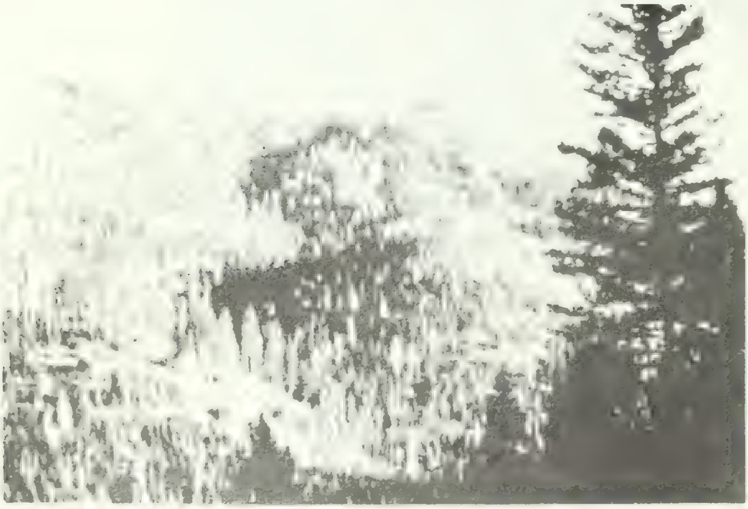


Figure 5.--Moderately dissected mountain slope landtype, with slope gradients of 45 to 60 percent. Drainages are spaced 500 to 1,500 feet apart. Fluvial lands are usually found between 3,500- to 6,000-foot elevation.

Figure 6.--A cryic landtype association that occurs near glaciated lands. The cryic lands are poor aquifers and provide little surface water for sustained streamflow.

Figure 7.--A typical stream type of the high-elevation valley train landtype, characterized by relatively uniform low flows, very stable banks and channels, and by low and rocky streambanks.

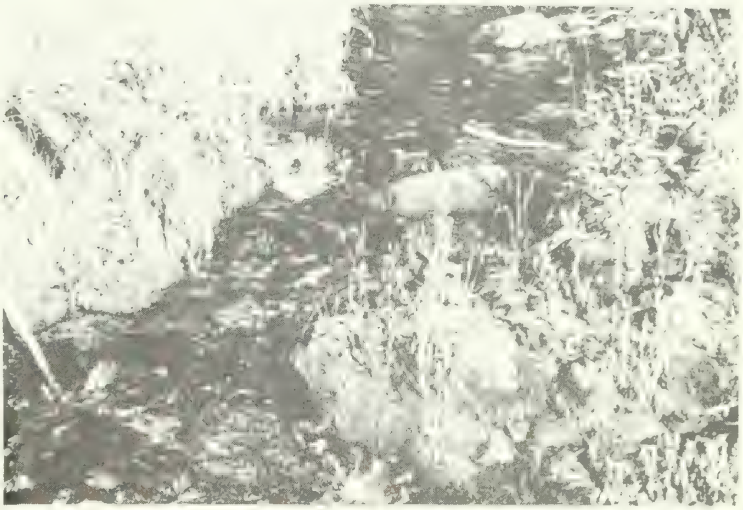
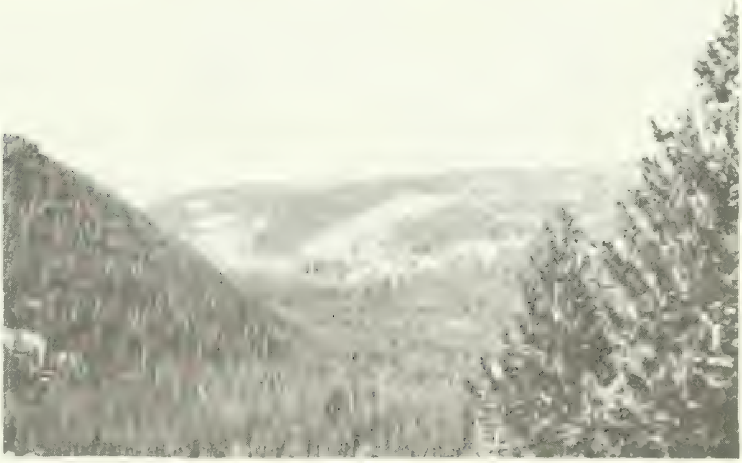


Figure 8.--A valley train landtype along the bottom and lower side slopes of the U-shaped glacial trough. The valley train lands buffer the stream from surrounding steep glacial trough lands and little surface water enters the stream.



## Water Column

Glaciated and cryic lands have much smaller streams than do fluvial or depositional lands, with glaciated streams tending to be the smallest (fig. 9). However, stream depths are almost identical among all landtype associations. Streams in glaciated and cryic lands have the highest pool-riffle ratio ratings, which agreed with their lower width-depth ratios. Streams in depositional lands have equal amounts of pool and riffle areas; streams in the fluvial lands are mostly riffles (fig. 10, 11, and 12).

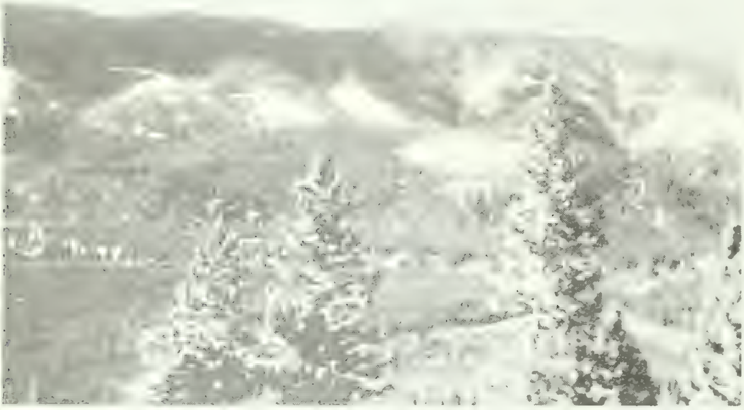


Figure 9.--Dissected fluvial landtype with logging clearcuts on faulted bench landtype. This entire floor is depositional, mainly composed of the moraine landtype.

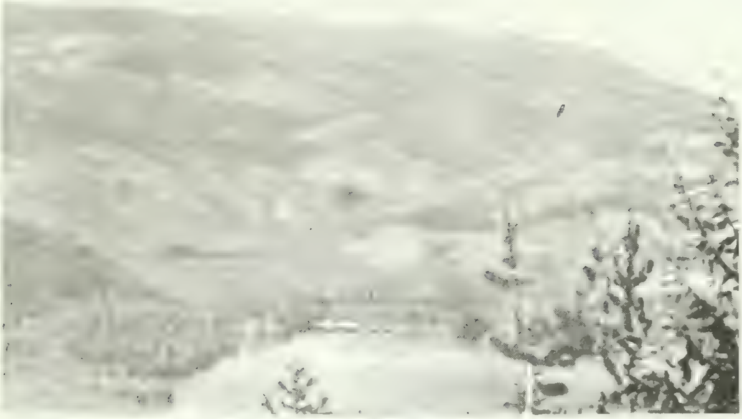


Figure 10.--An end moraine landtype bordering Warm Lake, with the surrounding mountainous areas mainly in the fluvial landtype association.

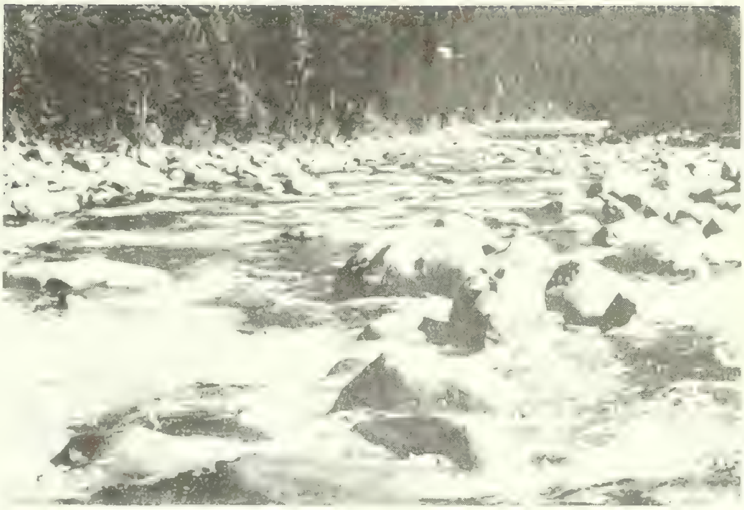


Figure 11.--Example of a stream channel dominated by boulders in an oversteepened canyon landtype downstream from the study area. The channel material in these lands averages larger in particle size than channel material found in most of the other landtypes.

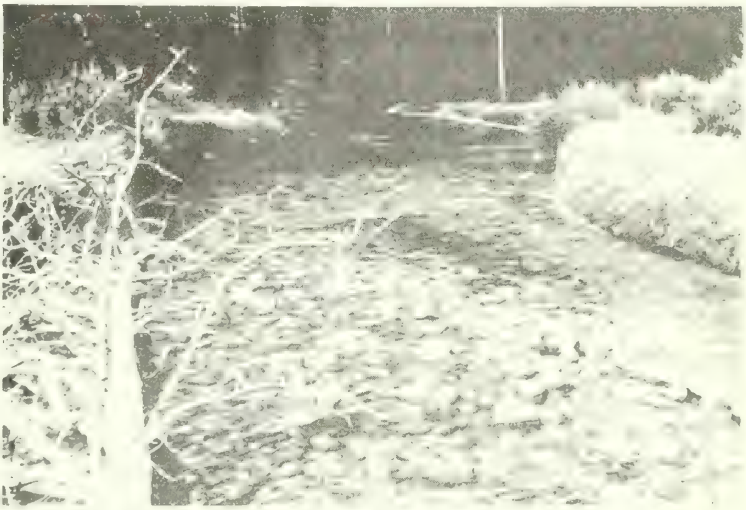


Figure 12.--An aquatic type in the depositional landtype association within the alluvial landtype influenced by upstream disturbed lands. These streambanks have good cover and stability, but the sediment transport rate is high, and gravel and rubble particles tend to be cemented together with fine sediment.

## Streamside Environment

Streambanks in the fluvial lands are largely controlled by the valley side slopes, which limited the capability of the stream to build bank pools. Streams in depositional and glaciated lands have more direct influence on their own banks. The high erosion rates, sediment types, and overland water flow in the cryic lands controlled streambank conditions.

## Channel Substrate

Stream channels in glaciated lands are mostly boulders and gravel while stream channels in cryic lands are mostly rubble and fine sediment. The differences are probably due to the differential effects of snow, ice, cold air temperatures, degree of rock weathering, and physical action of the glaciers. Stream channels in fluvial lands are dominated by boulders and rubble (fig. 11). Stream substrates in depositional lands are well-balanced in particle size (fig. 12).

## Stream Environments Within Landtypes

Twenty landtypes with distinctive soil, water, and landform were subdivided from the four landtype associations. Only eight landtypes had enough stream channel for adequate sampling to determine aquatic-fishery conditions (table 2). Of these eight landtypes (74 percent of the area), streams mainly ran through alluvial, valley-train, and dissected-mountain-slope lands.

Comparative measurments of stream structure, streamside environment, fish numbers, and fish species composition are shown in tables 3 and 4.

It was difficult to classify streams within certain landtypes in the same landtype association, but considerably easier among landtypes of different associations. Nevertheless, structural aquatic differences allowed satisfactory stratification in all associations. Platts (1976b) demonstrated the difficulty of determining factors that control fish standing crops and species composition. As we learn to identify and measure these factors, we will improve our comparisons of stream environments at the landtype level.

Among streams in depositional landtypes, only those on glacially deposited materials differ markedly from those on water-deposited materials. Therefore, the depositional lands were divided into two groups--one composed of materials laid down or worked by water, the other materials laid down or modified by ice. At lower levels of land classification (valley types) these differences in stream environments should automatically stratify.

Table 2.--*Landtypes containing or not containing perennial streams based on the sampling* [illegible]

| Landtype association | Landtype | Contains streams | |
|---|---|---|---|
| Glaciated | | | |
| | Cirque basin | yes | |
| | Faulted glacial scoured uplands* | occasionally | |
| | Glacial plastered mountain slope | | no |
| | Glacial scoured mountain slope* | | no |
| | Glacial trough | yes | |
| | Rocky ridge | | no |
| | Subalpine rim | | no |
| | Toe slope | | no |
| Cryic | | | |
| | Uplands | occasionally | |
| Fluvial | | | |
| | Dissected slope | yes | |
| | Faulted bench | | no |
| | Oversteepened canyon | | no |
| | River spur | | no |
| | Structural basin | occasionally | |
| Depositional | | | |
| | Alluvial | yes | |
| | Alluvial fan | yes | |
| | Glacial outwash | yes | |
| | Moraine | yes | |
| | Terrace | occasionally | |
| | Valley train | yes | |
| | Percent | 55 | 45 |

*The two landtypes are so similar that often they are considered the same.

Table 3.--*Stream conditions by landtype (95 percent confidence interval in parentheses)*

| Variable | Glacial landtype association | | | Fluvial landtype association | |
|---|---|---|---|---|---|
| | Cirque basin | Glacial trough | Glacial scoured uplands | Dissected slope | Structural basin |
| Gradients (percent) | 8.8 (0.9) | 13.4 (1.1 ) | 10.1 ( 2.8 ) | 6.4 (0.3 ) | 5.2 ( 0.3 ) |
| Width (feet) | 7 ( .5) | 10 (1.1 ) | 10 ( 2.7 ) | 15 (1.8 ) | 11 ( 1.2 ) |
| Depth (inch) | 5 ( .4 ) | 7 (0.9 ) | 10 ( 2.1 ) | 8 ( .3 ) | 8 ( .7 ) |
| Riffle (percent) | 43 ( .4 ) | 40 ( .9 ) | 50 ( 2.2 ) | 60 ( .5 ) | 45 ( 1.6 ) |
| Pool (percent) | 57 ( .5 ) | 60 (1.0 ) | 50 ( 1.5 ) | 40 ( .4 ) | 55 ( 1.9 ) |
| Pool rating (units) | 4.3 | 4.0 | 3.4 | 4.0 | 3.6 |
| Channel materials (percent) | | | | | |
| Boulder | 40 (5.4 ) | 50 (7.1 ) | 30 (13.3 ) | 36 (2.1 ) | 31 (10.0 ) |
| Rubble | 12 (3.0 ) | 22 (5.0 ) | 13 ( 7.2 ) | 30 (1.9 ) | 17 ( 6.1 ) |
| Gravel | 35 (4.9 ) | 24 (5.6 ) | 32 (11.7 ) | 15 (1.3 ) | 9 ( 3.5 ) |
| Fine sediment | 13 (3.5 ) | 4 (2.4 ) | 25 ( 9.9 ) | 19 (1.7 ) | 43 ( 9.6 ) |
| Streambanks (units) | | | | | |
| Cover | 1.8 ( .05) | 1.8 ( .04) | 1.5 ( .1 ) | 1.8 ( .02) | 1.7 ( .1 ) |
| Condition | 1.9 ( .03) | 1.9 ( .1 ) | 1.5 ( .1 ) | 1.6 ( .02) | 1.2 ( .1 ) |
| Type | 1.8 ( .1 ) | 2.0 ( .04) | 1.4 ( .1 ) | 1.9 ( .02) | 2.0 ( .0 ) |
| Channel elevation (feet) | 6941 | 5987 | -- | 4977 | 4788 |
| Sample size | 164 | 104 | 30 | 821 | 30 |

(con.)

Table 3.--[illegible] (con.)

| Variable | Depositional landtype association | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Alluvial | | Valley train | | Alluvial fan | | Moraine | | Terrace | |
| Gradient (percent) | 3.6 | (0.2 ) | 8.3 | (0.5 ) | 2.3 | (0.3 ) | 1.9 | (0.5 ) | 3.0 | ( 0.0 ) |
| Width (feet) | 17 | (1.0 ) | 13 | ( .5 ) | 13 | (1.1 ) | 12 | (1.7 ) | 26 | ( 9.3 ) |
| Depth (inch) | 8 | ( .5 ) | 8 | ( .3 ) | 7 | ( .7 ) | 6 | ( .7 ) | 16 | ( 2.6 ) |
| Riffle (percent) | 53 | (1.1 ) | 54 | ( .4 ) | 54 | (1.4 ) | 58 | (1.1 ) | 65 | ( 7.3 ) |
| Pool (percent) | 47 | (1.0 ) | 46 | ( .4 ) | 46 | (1.0 ) | 42 | (1.2 ) | 35 | ( 2.6 ) |
| Pool rating (units) | 3.7 | | 3.7 | | 3.8 | | 4.1 | | 4.0 | |
| Channel materials (percent) | | | | | | | | | | |
| Boulder | 15 | (2.8 ) | 41 | (2.4 ) | 16 | (5.7 ) | 22 | (9.1 ) | 78 | (14.3 ) |
| Rubble | 27 | (3.2 ) | 23 | (1.7 ) | 23 | (5.8 ) | 32 | (5.3 ) | 17 | (14.0 ) |
| Gravel | 32 | (3.9 ) | 16 | (1.5 ) | 21 | (5.1 ) | 33 | (5.8 ) | 2 | ( 5.8 ) |
| Fine Sediment | 26 | (3.4 ) | 20 | (1.9 ) | 40 | (7.4 ) | 13 | (3.8 ) | 3 | ( 6.6 ) |
| Streambanks (units) | | | | | | | | | | |
| Cover | 1.8 | ( .04) | 1.7 | ( .02) | 1.9 | ( .1 ) | 1.6 | ( .1 ) | 1.5 | ( .0 ) |
| Condition | 1.6 | ( .06) | 1.6 | ( .03) | 1.4 | ( .1 ) | 1.9 | ( .4 ) | 1.5 | ( .0 ) |
| Type | 1.8 | ( .05) | 1.8 | ( .03) | 2.0 | ( .05) | 1.9 | ( .04) | 1.8 | ( .4 ) |
| Channel elevation (feet) | 5614 | | 5675 | | 5422 | | 5530 | | 4310 | |
| Sample size | 243 | | 792 | | 67 | | 124 | | 5 | |

(con.)

Table 3.--*Stream conditions by landtype (95 percent confidence interval in parentheses) (con.)*

| Variable | Depositional landtype association | | Cryic landtype assocaition | |
|---|---|---|---|---|
| | Glacial outwash | | Cyric uplands | |
| Gradient (percent) | 2.7 | ( 0.5 ) | 6.5 | ( 2.4 ) |
| Width (feet) | 13 | ( 1.3 ) | 9 | ( 1.8 ) |
| Depth (feet) | 12 | ( 1.3 ) | 8 | ( 1.4 ) |
| Riffle (percent) | 38 | ( 1.9 ) | 44 | ( 1.3 ) |
| Pool (percent) | 62 | ( 1.8 ) | 56 | ( 1.6 ) |
| Pool rating (units) | 2.9 | | 3.3 | |
| Channel materials (percent) | | | | |
| Boulder | 8 | ( 7.1 ) | 12 | ( 6.9 ) |
| Rubble | 32 | ( 9.1 ) | 26 | ( 8.9 ) |
| Gravel | 14 | ( 5.9 ) | 20 | ( 8.2 ) |
| Fine sediment | 46 | (10.7 ) | 42 | (10.8 ) |
| Streambanks (units) | | | | |
| Cover | 2.0 | ( .0 ) | 2.0 | ( .03) |
| Condition | 1.4 | ( .1 ) | 1.6 | ( .1 ) |
| Type | 2.0 | ( .04) | 1.9 | ( .05) |
| Channel elevation (feet) | 5370 | | 6170 | |
| Sample size | 30 | | 55 | |

Table 4.--*Average number of fish by species per station by landtype association*

| Species | Landtype association | | | |
|---|---|---|---|---|
| | Glaciated | Cryic | Fluvial | Depositional |
| Brook trout | | | 0.1 | 0.3 |
| Chinook salmon | | | .6 | 2.0 |
| Cutthroat trout | | | .1 | .1 |
| Dace | | | | .01 |
| Dolly Varden | | | .3 | .5 |
| Rainbow trout | 0.2 | | 3.3 | 1.2 |
| Sculpin | | | .1 | .2 |
| Whitefish | | | | .1 |
| Other | | | .1 | .02 |
| Total fish | 0.2 | | 4.6 | 4.5 |
| Sample number | 6 | 0 | 108 | 168 |

# ANALYSIS BY BASIC COMPONENT

## Stream channel Gradients

Except for valley train lands, landtypes composed of depositional materials have low channel gradients; alluvial fan lands have the lowest channel gradients. Valley train lands are ice-formed, which probably accounted for steeper stream gradients.

## Water Column

Terrace and oversteepened canyon lands are adjacent to the larger streams, so larger streams intercepting these lands were expected. Stream widths and depths between landtype associations were different but similar by landtype. There should be some correlation between stream width and depth as one is influenced by the other. When landtype and landtype phase descriptions and delineations are more refined, it will be easier to determine if similar landtypes have similar stream width and depths. Cryic lands typically contain few streams, and those are small. Pool-riffle ratios were not significantly different among all landtypes in the depositional lands. Streams in glaciated and cryic lands have a higher pool-riffle than streams in dissected mountain slope lands.

## Channel Substrate

Stream channel materials showed more differences between landtype association than by landtype; however, channel materials in valley train lands differed from materials in streams in landtypes also composed of depositional materials. The difference is probably due to glacial influence in the valley train lands. Percentage of boulder was higher and fine sediment was lower in streams flowing through glaciated landtypes than in stream channels in cryic lands, where materials had been more stationary.

Stream channels in morainal lands contain the highest percentage of rubble because of the nature of the soil moved by the glacier. Cirque basin lands have the lowest amount of rubble in their stream channels but have the highest amount of gravel. Cirque basin land streams have the highest amount of gravel of all landtypes. Glaciation and nivation are probably the main processes responsible for creating rubble and gravel for these streams.

Channels in landtypes that produce abundant sediment (cryic, dissected slope, and structural basin) and have low channel gradients (glacial outwash and alluvial fan) have more fine sediment in their channels than gravel. The river spur and oversteepened canyon landtypes are high producers of channel sediment to down-drainage streams. In the study area, landtype proximity to streams and the types of sediment sources (roads, fire, etc.) directly affect streams.

## Streamside Environment

Streambank stability is influenced by vegetative cover, but this was not properly inventoried or classified within landtypes. Streambank stability and cover usually rated good to excellent throughout the study area; thus differences were small between different landtypes.

## Summary

It was not possible to completely classify the stream environment at the landtype level, perhaps because of inadequate sampling, inadequate description of the stream environment, an inadequate landtype classification, or perhaps all three factors. Improving our ability to map and define land units and describe stream environemnts at the landtype level will allow us to classify fishery environments with more accuracy. Most of the stream environments within landtypes can now be described, classified, and worked into the Land System Inventory at landtype and landtype association levels. As research refines this methodolgy and applies it to the valley type and riparian type levels of land stratification, the differences in stream environments at this level should become even more distinct.

# Fisheries Within Landtype Associations

Only the cryic landtype association contained streams incapable of producing good fish populations. The strongly glaciated lands were also almost barren of stream fish, with fish occurring only in the glacial trough landtype (tables 4 and 5). In good lake habitat, fish thrive in high-elevation glaciated and cryic lands despite severe winters; however, fish cannot survive in shallow streams during harsh winters.

Streams in depositional and fluvial lands supported almost all of the fish. Streams in the depositional lands were the most productive, although these lands accounted for only 10 percent of the area. Chinook salmon, rainbow trout, cutthroat trout, Dolly Varden, brook trout, and sculpin were found in both the depositional and fluvial landtype associations; rainbow trout were the only species found in the glaciated lands. Sculpin preferred the lower gradient streams in the depositional lands.

# Fisheries Within Landtypes

Only eight of the 20 landtypes had streams supporting fish populations of any importance. Although fish were collected in two of the eight landtypes, only one stream in the study area failed to produce fish in the sampling program. All other streams supported fish because most of them flowed through or were influenced by more than one landtype. Streams draining multiple landtypes had higher fish standing crops and more fish species than did streams that drained only a single landtype.

In glaciated lands, only streams in the glacial trough landtype supported fish. Landtypes in the depositional lands contained the most productive streams, with streams in the alluvial lands containing the highest fish standing crops. Because of the higher miles of stream in the valley-train and dissected-mountain-slope landtypes, more fish occur in these two landtypes than the others combined.

Table 5.--*Average number of fish by species per station by landtype association*

| Species | Alluvial | Terrace | Glacial outwash | Valley train | Alluvial fan |
|---|---|---|---|---|---|
| Brook trout | 0.8 | | 0.6 | 0.1 | |
| Chinook salmon | 7.1 | 4.0 | | .1 | 5.3 |
| Cutthroat trout | | | | .2 | |
| Dace | .1 | | | | |
| Dolly Varden | .6 | | | .7 | .3 |
| Whitefish | .4 | | | | |
| Rainbow trout | .8 | 6.0 | .2 | 1.4 | .5 |
| Sculpin | .4 | | | | .3 |
| Other | .1 | | | | |
| Total fish | 10.3 | 10.0 | 0.8 | 2.5 | 6.4 |
| Sample number | 35 | 1 | 5 | 102 | 12 |

| Species | Moraine | Cryic uplands | Cirque | Glacial trough | Dissected mountain slope |
|---|---|---|---|---|---|
| Brook trout | 0.3 | | | | 0.1 |
| Chinook salmon | 1.3 | | | | .6 |
| Cutthroat trout | | | | | .1 |
| Dace | | | | | |
| Dolly Varden | .1 | | | | .3 |
| Whitefish | | | | | |
| Rainbow trout | 2.2 | | | .7 | 3.3 |
| Sculpin | .5 | | | | .1 |
| Other | | | | | .1 |
| Total fish | 4.4 | | | .7 | 4.6 |
| Sample number | 13 | 4 | 8 | 3 | 108 |

Chinook salmon, rainbow trout, cuttroat trout, Dolly Varden, brook trout, and sculpin occurred in streams in landtypes occuring in both the depositional and fluvial landtype associations. Mountain whitefish and dace occupied streams only in the alluvial fan landtypes. Chinook salmon were found mainly in the alluvial and alluvial fan landtypes.

Sculpin preferred lower channel gradients in depositional landtypes, but were not found in the valley train landtype. The predominance of high channel gradients in these streams could have been a factor causing their absence.

The west slope cutthroat trout, widely acknowledged to be a species declining in numbers and range, mainly occupied the valley-train lands. Streams in this landtype were still in the natural state. Nevertheless, the density of the cutthroat trout population was lower than those of rainbow trout or Dolly Varden, and only twice that of chinook salmon and brook trout.

The fact that cutthroat trout were found to occupy only two landtypes could attest to the difficulty this species has in competing with other native as well as exotic species. Brook trout, an exotic species, have much more success in extending their range and numbers across certain landtypes.

The results emphasize the critical problems the west slope cutthroat trout confronts in holding its range and numbers within selected landtypes. The problems may become even more complex as land uses become more diverse and other native or exotic fish species are introduced.

## DISCUSSION

The Land System Inventory allows fishery biologists to combine stream descriptions with information of other disciplines. The combined information can then be systematically worked into an inventory of land units appropriate for land use planning. Working aquatic information into the Land System Inventory is important: this system is the major tool for decisionmaking on National Forest lands. Wendt, Thompson, and Larson (1975) found that when considering the seven categories of landform stratification, the landtype association and landtype levels proved to be the most useful to National Forest planning. The landtype level is the basic level of the Land Systems Inventory now being used at the Ranger District level of planning. This study shows the aquatic system can fit into either of the two levels.

The basic framework for combining the aquatic information outlined in this study can also be used to enter the fishery system into lower levels of the Land Systems Inventory as they are developed. Hopefully research will develop the refinement needed in aquatic methodologies that will allow the fisheries to enter into all levels of land use planning. The valley type and aquatic type levels should have the highest research priority.

Fishery biologists should settle on a common approach to land use planning that has credibility, reliability, and preciseness. This study shows that it is possible.

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# APPENDIX A

## A. Aquatic Environment-Fishery Information at the Landtype Association Level

## GLACIATED LANDS

### Geomorphic Description

Glaciated lands are found above 6,000 feet (1,830 m) in elevation and occur mainly in the headwaters of the South Fork Salmon River and its tributaries. They include 96,830 acres (39,180 ha) and make up 38 percent of the study area.

These lands, shaped by alpine glaciation, are characterized by straight, U-shaped glacial valleys and a parallel drainage system. Common landforms are cirque basins, headwalls, rocky ridges, and weakly expressed horns.

### Aquatic Environment

Streams in the glaciated lands average much smaller and shallower than those in fluvial or depositional lands. They are dominated by pools of poor quality, have high pool-riffle ratios, low width-depth ratios. Channels are dominated by boulders and gravel with low amounts of fine sediments and rubble. These channels contain a higher percentage of gravel and less rubble and fine sediments than channels of other landtype associations.

Stream channels are the highest in elevation of any associations with the heaviest winter icing and the coldest summer water temperatures. Streams in this association lie in U-shaped valleys with wide buffer zones between them and the valley slopes. This results in very little overland water flow carrying sediment into the streams.

Channel gradients are steeper than channels in the other landtype associations because of hanging valleys and the high gradient of the horizontal stairsteps of the glaciated valley. Streambanks are very stable and contain many boulders. Streamside cover is mostly trees and brush.

Low dissolved solids result in clear, infertile water. Streamflow fluctuates less than in any of the other landtype associations.

### Fisheries

Fish standing crops and the number of fish species present are extremely low. Glacial trough landtypes supported most of the fish population. Rainbow trout were the dominant species, but the anadromous form of the rainbow trout (steelhead trout) probably does not occur in these lands. Salmon probably never enter these lands. Cutthroat trout and Dolly Varden may inhabit streams of this landtype association, but populations would be extremely low.

# CYRIC UPLANDS

## Geomorphic Description

Cryic lands form a complex or transition zone below or adjacent to the glaciated lands and include 17,180 acres (6,950 ha), or 7 percent of the study area. Effects of ice and permanent snowfield action are localized. Soil and rock were not carried by major ice currents, as was the case of the glaciated lands. As a result, the lands have subdued topography. Slopes are more gentle and mostly convex in shape.

In most cases, the cryic lands have only weakly expressed drainage development. This is partially due to the dominant slope-forming processes that are thought to be presently active on these slopes. Cryic landscapes are at elevations where nivation, freezing, thawing, wetting, and drying make mass wasting the chief process by which materials are or were moved downslope. These processes keep replacing materials that have been removed by overland flow.

## Aquatic Environment

The few streams on cryic lands are small and narrow, but have the lowest width-depth ratio of all streams in the study area. The streams are about equal in size to those in the glaciated lands but much smaller than streams in the fluvial or depositional lands.

Cryic areas have constant subsurface frost churning and soil movement; streams are few and thousands of feet apart. Channel gradients are steep and channel elevations high, but less so than in glaciated lands.

Riffles are scarce. The average quality of pools rated higher than the other landtype associations, which could be due to the lower ratio of width to depth. Because streams mostly face south, water temperatures are higher than those in glaciated lands.

High slope erosion rates result in channels dominated by fine sediments, with the percentage of the fine sediments higher and percentage of boulders lower than in any other landtype association. Percentage of rubble is higher and gravel is lower than in streams in the glaciated lands.

Streambank cover is mostly trees, but stability of the bank rates only good because of the surrounding high rates of soil erosion and soil sliding. Streams are only slightly entrenched and lie in shallow valleys that are between U- and V-shaped. The limited buffer zone near the stream permits direct overland flow of eroded soils into the streams.

## Fisheries

If fish are present at all, numbers and number of species are extremely low. It is doubtful if anadromous salmon and steelhead ever use this area.

# FLUVIAL LANDS

## Geomorphic Description

Fluvial lands, located along the lower mountain slopes, include 114,260 acres (46,240 ha), or 45 percent of the study area. Stream-cut lands provide 80 percent of the naturally occurring sediment reaching the streams.

Seventy-eight percent of the logging and 69 percent of the road construction have been on fluvial lands. These lands usually occur below the 6,000-foot (1,830 m) elevation, are characterized by steep, V-shaped valleys, and have a strongly expressed drainage system.

The dominant geomorphic process is running water, but mass wasting, uplift, faulting, and structural control have also contributed to the shape of these lands.

## Aquatic Environment

Streams in the fluvial lands have fairly high channel gradients with a high width-depth ratio, as evidenced by the prevalence of riffles. Percentage of pool is lower and percentage of riffle is higher than in streams of any other landtype association. Although the streams are wide, they tend to be shallow, with poor quality pools.

Stream channels are mainly boulders and rubble, with fine sediments exceeding gravel, which reflects the high rate of soil erosion from the slopes. Streamside cover is mostly trees and brush; bank stability is rated only good.

Streams lie in V-shaped valleys. Very little buffer (floodplain) lies between the stream and valley sides, which permits direct inflow of surface waters and sediment during snowmelt and storms.

Streams in this association have the lowest channel elevation and because of well-weathered bedrock, dissolved solids are higher than in streams of any other landtype association. Therefore, these streams with higher temperatures and nutrients are slightly more fertile than streams in the other associations.

## Fisheries

Rainbow trout were the dominant species, followed by chinook salmon, Dolly Varden, cutthroat trout, brook trout, and sculpin. Fish averaged about one per 10 feet (3 m) of stream. Cutthroat trout occurred at only half the population density of which they occurred in the valley train landtype.

# DEPOSITIONAL LANDS

## Geomorphic Description

The depositional lands of alluvial or morainal origin account for 25,930 acres (10,490 ha) or 10 percent of the study area. These lands were formed by water and glacial deposits and occur mainly as small land units throughout the study area. Except in the Warm Lake Basin, depositional lands make up a small portion of the study area.

These lands are extremely important to the aquatic environment because they include (1) both sides of streams in the U-shaped glacial trough, (2) terraces adjacent to streams, (3) the morainal, glacial outwash and fluvial deposits, and (4) the glacial deposits that compose the valley train landtype.

### 1. Water Deposited

*Aquatic environment.*--Those lands formed by soils deposited by water, within the depositional landtype association, contain the largest streams in the study area and have low channel gradients. Stream width-to-depth ratios are high. These streams build their own banks, but pool quality is still poor, and riffles dominate the stream.

Stream channels have very low percentage of boulders, a high percentage of fine sediments, and abundant gravel and rubble. The high amount of channel gravel, combined with low gradient channel reaches, provides the best salmonid spawning environment in the area.

The wide, flat floodplain between the stream and valley slopes acts as a buffer zone restricting overland water flow and sediment from entering the streams. However, streams usually receive high amounts of sediment from upstream fluvial, glaciated, and cryic lands. Streamside cover is dominated by trees and brush; stability of streambanks is good.

*Fisheries.*--Streams in these lands contained all of the fish species recorded and the highest number of species of any association. Chinook salmon relied more on these streams for spawning and rearing than on streams in any other landtype association.

Chinook salmon were the dominant species followed by rainbow trout, brook trout, sculpin, Dolly Varden, mountain whitefish, and dace. Cutthroat trout numbers were low. Sculpin numbers were higher in these streams than in streams of any of the other landtype associations.

### 2. Ice-Shaped or Ice-Deposited Land Association

*Aquatic environment.*--The depositional lands were separated into the water-deposited and the ice-deposited groups to isolate the streams in valley train landtype which do not resemble the other streams in the depositional association. In doing this, the moraine land streams had to be included with the valley train streams even though they are intermediate between the two groups. Because the valley train streams make up the bulk of the streams in the ice-shaped or ice-deposited group, stream description refers mainly to those in the valley train landtype.

Stream gradients are steep; channels are mainly boulders and are low in gravel and fine sediments. Riffles predominate, with occasional poor quality pools.

The valley train streams usually occur in wide, U-shaped valleys, with wide buffer zones lying between the streams and side slopes. Overland surface water flows and direct sediment entering the stream are low. Streamside cover is dominated by brush and trees.

*Fisheries*.--Rainbow trout were the dominant species, followed by Dolly Varden, cutthroat trout, brook trout, and chinook salmon. Dace, mountain whitefish, and sculpin were lacking, or populations were extremely low. This was the main landtype association used by the cutthroat trout; however, they averaged only one per 250 feet (76 m) of stream.

Chinook salmon used the lower elevation stream sections for spawning and rearing. Sculpin were lacking, which means these streams may not meet some of the environmental needs of other fish. Sculpin were usually found in the geomorphic types having relatively high densities of fish populations.

# APPENDIX B

## Aquatic Environment-Fishery Condition at the Landtype Association Level

## GLACIATED LANDTYPE ASSOCIATION

### Cirque Basin

*Geomorphic description.*--Cirque basins are amphitheater-like basins, found at the heads of most of the glaciated valleys. Some basins contain small lakes while many of the larger cirque basins have small areas of wet alluvial lands near the lakes. Common inclusions are narrow strips of valley train and toe slope lands.

*Aquatic environment.*--Stream channel gradients are about equal to channel gradients in valley train landtypes, probably because stream channels are stepped, and often very steep. Cirques produced the smallest, shallowest streams studied.

Streams have more pool than riffle, which is different for batholith streams. The pool-riffle ratio is close to one (50 percent pool, 50 percent riffle) with pool quality being very poor. The stream channel is mostly boulders; very little rubble and fine sediment is present.

Bedrock is hard and does not readily break down to the particle size of bedload materials. For some unknown reason (possible nivation), gravel content was high in the stream channels. Streambank environments are nearly excellent. These streams have the highest-elevation perennial channels in the study area.

*Fisheries.*--No fish were collected, and if populations do exist, they would be very low because of extreme winter conditions.

### Glacial Plastered Mountain Slope

*Geomorphic description.*--These slopes have been modified by glacial material deposited rather than stripped away by glacial scouring. Slopes are usually benched, with fairly thick mantles of soil. Most of these lands are in glacial troughs and contain considerable rounded rock fragments typical of lateral moraines.

*Aquatic environment.*--The steepness and location of these lands keep perennial streams from developing or entering.

*Fisheries.*--This land type did not contain fish.

### Glacial Scoured Mountain Slope

*Geomorphic description.*--These lands consist of steep, benchy mountain shoulders which have been scoured by alpine glaciers. They generally occur downstream from the cirque basin lands and are between subalpine rim lands and glacial trough lands. They are similar to the smooth and weakly dissected glacial trough lands. They do, however, have up to 30 percent rock outcrop, and, as a result of glacial scouring, a thinner mantle.

*Aquatic environment.*--Because of the steepness and location, these slopes contain few perennial streams over 4 feet (1.2 m) in average width.

*Fisheries.*--These lands did not contain fish.

Glacial Trough

*Geomorphic description.*--Glacial trough lands occupy the side slopes of the glacial-formed U-shaped troughs typical of alpine glaciation. The preglaciation slopes have been oversteepened by the ice actions of glaciers. The stream drainage patterns on these lands are usually parallel, compared to the dendritic stream pattern in the fluvial lands.

*Aquatic environment.*--Because of the steepness of the glacial trough lands, their streams have steeper channels than streams in other landtypes. Stream channels are dominated by boulders, while fine sediments are almost nonexistent because of the hard nonweathered bedrock, high channel elevations, and high channel gradients. Streambank environments are almost excellent in quality.

*Fisheries.*--Rainbow trout inhabited this geomorphic type but in very low numbers. Winter conditions are extreme, thus this geomorphic type, with its small streams, does not lend itself to producing many fish.

## Rocky Ridge

*Geomorphic description.*--These lands occur mainly in the higher elevation glaciated lands and included the highest ridges, upper slopes, and extremely rocky spur ridges. Talus slopes are common, and the percentage of rock outcrop commonly exceeded 50 percent Slopes are quite steep, often being 90 percent or more.

*Aquatic environment.*--The steepness and location of these lands preclude streams from occurring.

*Fisheries.*--These lands contained no fish.

## Subalpine Rim

*Geomorphic description.*--This area consists of subalpine mountain shoulders, mainly on south- and west-facing slopes. These shoulders were not subjected to severe ice plucking and scouring and since glaciation have not been dissected by streams. The slopes are relatively smooth, straight to weakly convex, and extended from ridgetops to as much as 1,000 feet (305 m) in elevation downslope. The adjacent landforms on north- and east-facing slopes are commonly rocky cirque headlands and cirque basins.

*Aquatic environment.*--Because of the steepness and location of these lands, streams do not occur.

*Fisheries.*--Fish do not occur in these lands.

## Faulted Glacial Scoured Uplands

*Geomorphic description.*--These lands consist of severely scoured glacial uplands that average 50 percent rock outcrop, and have been faulted prior to and probably since glaciation. The area is covered by huge faulted granitic rocks, some as high as 30 to 40 feet (9 to 12 m), with isolated pockets of soil between them.

*Aquatic environment.*--The steepness and location of these lands preclude all but a few isolated streams.

*Fisheries.*--Fish did not occur in these lands.

### Steep Rocky Cirque Headlands

*Geomorphic description.*--These lands are the steep, rocky, ice-plucked cirque headlands of minor drainages, located above the cirque basin. Their granitic bedrock is hard, unweathered, nonspalling, and moderately fractured. The aspect is predominantly north; the elevation between 7,000 to 9,000 feet (2,130 to 2,740 m); and the slope gradient between 60 to 75 percent.

*Aquatic environment.*--Because of the steepness and location of these lands, they do not contain streams.

*Fisheries.*--Fish did not occur in these lands.

## CRYIC LANDS

### Cryic Landtype

*Geomorphic description.*--Cryic uplands were not subjected to the scouring action of the nearby glaciated lands and are the result of the climatic changes brought about by glaciers. These lands are thought to have been formed by the processes and effects of permanent snow and ice field action; any movement of materials was local. Generally, they have not been dissected to any great degree by fluvial processes.

*Aquatic environment.*--Stream channel gradients are lower than in any of the glaciated lands. Streams had a difficult time forming in these lands because of the high percolation rates and their landscape position. The few streams that do form are very small.

Most of the stream is made up of pool, with a pool-riffle ratio about 1:1. Boulders are lacking in the channels, probably due to the weathered bedrock. These lands are high producers of fine sediment, which is plentiful in stream channels.

The streambank cover is dominated by trees, but the high amount of incoming fine sediments lowers the bank stability. Stream channels are at high elevations because they occur in ice-modified lands.

*Fisheries.*--Fish could not be found in these streams. If fish do exist, numbers would be extremely low.

## FLUVIAL LANDS

### Faulted Bench Lands

*Geomorphic description.*--This special group of lands results from remnants of block (normal) faulting activity. The block faulting resulted in low, benchlike ridge systems which, in many cases, have been modified by glacial outwash deposits and are moderately to weakly dissected by streams.

Faulted bench, structual basin, and river spur are not true fluvial types but are included under fluvial because, since their formation, they have been altered or formed by fluvial processes.

*Aquatic environment.*--These lands composed a small portion of the study area and contain a few small streams.

*Fisheries*.--Streams in these lands contained no fish.

## Dissected Mountain Slope Lands

*Geomorphic description*.--Dissected mountain slope lands consist of slopes incised by streams. Stream cutting was the dominant slope-forming influence. Streams usually form a dendritic drainage pattern.

*Aquatic environment*.--The streams flow in V-shaped valleys, with little buffer in between the stream and the slopes to stop surface water and sediment from directly entering the stream. Channel gradients are high but not as high as stream channels in the glaciated lands. Usually, streams receive water from streams at higher elevations and tend to be larger than streams in other geomorphic types.

Streams are mostly riffles; pool quantity and quality is low. Because of the steep side slopes of the valley and channel downcutting, boulders and rubbble dominate the stream channels. Percentage of fine sediments is higher than gravel because of the high rate erosion. The streambanks have good vegetative cover and stability.

*Fisheries*.--These streams averaged about 1 fish per 10 feet (3 m) of stream. Populations were mainly rainbow trout followed by chinook salmon, Dolly Varden, cutthroat trout, brook trout, and sculpin. Besides valley train lands, this was the only landtype cutthroat trout were found in.

Adult chinook salmon use the lowest elevation sections of the streams for spawning and the young for rearing. Rainbow trout averaged 1 fish per 15 feet (4.5 m) of stream.

## Oversteepened Canyon Lands

*Geomorphic description*.--These lands range from steep to extremely steep. They include the moderately to strongly dissected mountain slopes adjacent to the SFSR. They contain second or third order streams that flow directly into the main river; therefore, there was a difference of two or four stream orders between streams in this geomorphic type and the SFSR.

*Aquatic environment*.--No sampling was done in these lands because they made up only a small portion of the study area. Streams formed completely within this geomorphi type are usually short, have extremely steep channel gradients, and have little productive habitat to offer the fishery. This description is not valid for the SFSR which flows through segments of oversteepened canyon lands.

*Fisheries*.--Streams other than the SFSR did not provide the habitat required by fish.

## Structural Basin Lands

*Geomorphic description*.--These lands have been modified on site or displaced from their original position by faulting, and therefore occupy a lower position in elevation than they previously occupied.

*Aquatic environment*.--Because streams were scarce, sampling was minimal. The streams are usually located in the headwaters and therefore were very small.

*Fisheries*.--These small streams are only capable of supporting low numbers of small fish.

### River Spur Lands

*Geomorphic description.*--The river-spur lands are knoll-like ridge remnants, seldom more than 40 acres (16 ha), and adjacent to the SFSR. They now occur in positions formerly occupied by the river. They were separated from the main mountain slopes by the force of the river cutting through fractures and least-resistant rocks.

*Aquatic environment.*--These isolated tracts do not contain streams and only border streams originating in other geomorphic types.

*Fisheries.*--These lands contained no fish.

## DEPOSITIONAL LANDS

### Alluvial Fan

*Geomorphic description.*--The alluvial fans are cone-shaped alluvium that was deposited by streams flowing onto a level plain or meeting a stream with less energy.

*Aquatic environment.*--Streams have exceptionally low channel gradient because the fan developed in areas of gentle slope. Stream size is comparable to other landtypes. Riffle makes up slightly more than half the stream making the pool-riffle ratio about 1:1.

The alluvial fan contains high amounts of boulders. Therefore, stream channels are dominated by boulders. Streambank vegetation is abundant but the material of the fan causes reduced streambank stability. Channel elevations average about the same as channel elevations averaged for all streams sampled.

*Fisheries.*--Chinook salmon use these low gradient streams for rearing and spawning. Salmon were the dominant species, followed by rainbow trout, Dolly Varden, and sculpin. Chinook salmon averaged 1 fish per 10 feet (3 m) of stream, while rainbow trout only averaged 1 fish per 100 feet (30 m) of stream. The occurrence of sculpin indicated a favorable environment for other fish.

### Alluvial Lands

*Geomorphic description.*--The alluvial lands border streams and include river wash, bottom lands, and first-terrace land positions. They also occur in high mountain meadows where there may be alluvial deposits caused by high water tables.

*Aquatic environment.*--Streams in this geomorphic type are large, with low channel gradients compared to other study streams. The streams contain slightly more riffle than pool, with a pool-riffle ratio close to 1:1. The stream channel is slightly low in boulders and slightly high in fine sediments, with equal amounts of rubble and gravel.

Streambanks have good cover and stability. Channel elevations are fairly high at 5,614 feet (1,711 m) average, because these lands occur mainly in the headwaters of the SFSR drainage.

*Fisheries.*--Fish numbers are high, with an average of 1 fish per 5 feet (1.5 m) of stream. Chinook salmon were the dominant species, followed by brook trout, rainbow trout, Dolly Varden, mountain whitefish, sculpin, and dace. More fish species occurred in this geomorphic type than in any other type.

Cutthroat trout were not found in the sampling program and if they do occur populations are extremely low. The low channel gradients and abundant sources of channel gravel resulted in the best spawning environments found for salmonids in any of the geomorphic types. These lands contain the most productive fish habitat of the 20 landtypes.

## Moraine Lands

*Geomorphic description.*--The ground moraines have been reworked by running water and have had glaciated outwash materials deposited on them. These lands range from nearly level to gently sloping, with low hummocky relief. Depressions are generally noncobbly for the first few feet in soil depth; soils are generally nonstratified.

*Aquatic environment.*--Stream channel gradient is low because the glaciers deposited morainal materials in areas with gentle topography. Stream size and channel elevations are about the same as the average for all study streams combined. There is slightly more riffle than pool, with a pool-riffle ratio close to one.

Pool quality is poor. Possibly because of the morainal type materials, channel substrates are high in percentage of gravel and rubble and low in fine sediments. Streambank stability is good, but streamside vegetative cover is less abundant than the average for all study streams.

*Fisheries.*--Rainbow trout were the dominant species collected, followed by chinook salmon, sculpin, brook trout, and Dolly Varden. Sculpin numbers were higher per length of stream than found in any other geomorphic type. Chinook salmon use the area for spawning and rearing. Streams average about 1 fish per 10 feet (3 m) of stream.

## Glacial Outwash Lands

*Geomorphic description.*--This landtype is similar to the moraine landtype and includes the smooth, flat landscape in the Warm Lake basin and the terrace lands adjacent to the SFSR. Materials in the outwash lands are stratified while the materials in the moraines are well mixed. Also, glacial outwash lands have a smooth micro-relief compared to the hummocky micro-relief of the moraine land.

*Aquatic environment.*--These lands are restricted to the Warm Lake basin and contain only a few short sections of stream.

*Fisheries.*--Fish numbers were low, averaging less than 1 fish per 50 feet (15 m) of stream. Brook trout was the dominant species followed by rainbow trout. Sculpin, most plentiful in streams having the most fish per length of stream, were not collected in these lands.

## Valley Train Lands

*Geomorphic description.*--Valley train lands comprise the bottoms and lower side slopes of the U-shaped glacial troughs.

*Aquatic environment.*--Although this landtype made up only 4.5 percent of the study area, streams in this geomorphic type are the most important of the streams in the higher elevations. Channel gradients are high because the ice-deposited materials have higher valley gradients than water-deposited materials. Because of the wide U-shaped glaciated valley, the streams have excellent buffer zones to eliminate overland surface flows and sediment from the valley slopes from entering the stream.

Streams have slightly more riffle than pool, with a pool-riffle ratio close to 1:1. Pool quality is better than for the average study stream. Stream channel materials are dominated by boulders and low in gravel.

Fine sediments in the channel are high for streams having such high channel gradients. Streambank cover and stability is good; channel elevations are high because all streams are in glaciated valleys.

*Fisheries*.--Fish averaged 2.5 per 50 feet (15 m) of stream. Rainbow trout was the dominant species followed by Dolly Varden, cutthroat trout, brook trout, and chinook salmon. This geomorphic type was the mainstay of the cutthroat trout and contained most of the Dolly Varden population. Sculpin were absent, possibly because of the high channel gradients causing high stream power.

## Terrace Lands

*Geomorphic description*.--These flat to gently sloping lands were previously deposited by the larger streams. The deposits were once entrenched and dissected; they are now only remnants of once larger landforms. These river terraces were probably deposited as glacial outwash during one of the Pleistocene glacial intervals and then left in their present elevated position by the entrenchment of streams.

*Aquatic environment*.--Because these lands now hang on the valley sides, they do not form or offer much passage to streams except along the main river. Some of these lands are still low enough to be adjacent to the stream.

*Fisheries*.--The few streams that do contact these lands are large. Only one station was in terrace lands, and it recorded 1 fish per 5 feet (1.5 m) of stream. Rainbow trout and chinook salmon were the only fish recorded.

## Toe Slope Lands

*Geomorphic description*.--Lands form the toes of glacial troughs and dissected mountain slopes. Soil are primarily colluvial deposits at the base of the higher adjacent slopes. Slopes are well vegetated (predominantly timber) and are straight to concave. Slopes have 30 to 55 percent gradient and are 50 to 1,000 feet (15 to 305 m) long, at elevations of 4,000 to 5,500 feet (1,220 to 1,680 m). Toe slope land occurs in units that are large enough to delineate consistently at the toes of glacial troughs and mountain slopes.

*Aquatic environment*.--The location and composition of the soils usually precludes perennial streams, which eliminated them from the random sampling system.

*Fisheries*.--These lands did not support fish.

Platts, William S.
1979. Including the Fishery System in Land Planning. USDA For. Serv. Gen. Tech. Rep. INT-60,37 p. Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.

Presents a system for integrating streams and fisheries into the Land Systems Inventory--the geomorphic analysis used by the USDA Forest Service to determine type and intensity of land use that can be permitted without environmental damage. As originally designed, the Land Systems Inventory did not adequately consider the aquatic environment and fisheries. The Land Systems Inventory as now amended is now suited to classifying and audocating uses over large areas of mountainous terrain, including terrestrial and aquatic environments.

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